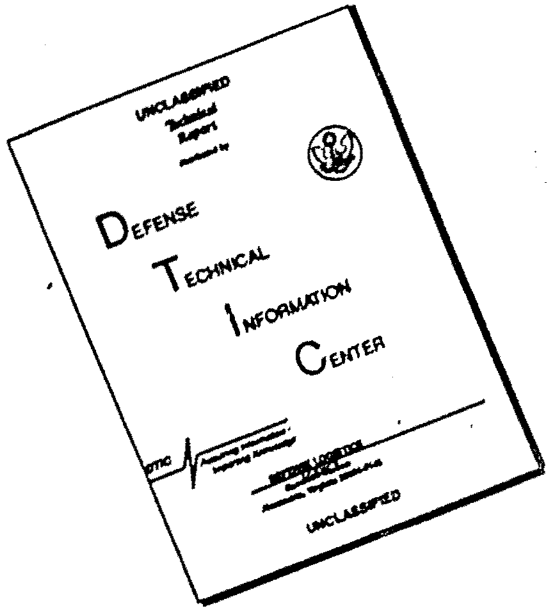
MAB-207-M

MICROMECHANICS OF FIBROUS COMPOSITES

MATERIALS ADVISORY BOARD

National Academy of Sciences—
National Research Council
Washington, D. C.

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

MATERIALS ADVISORY BOARD

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL ACADEMY OF SCIENCES-NATIONAL RESEARCH COUNCIL

Chairman

Dr. Walter R. Hibbard, Jr. (1966)
Manager, Metallurgy & Ceramics Research Department
General Electric Company
P. O. Box 1088
Schenectady, New York 12301

Members

Professor John C. Bailar, Jr. (1966)
Department of Chemistry & Engineering
The William Albert Noyes Laboratory
The University of Illinois
Urbana, Illinois

Dr. J. H. Crawford (1969)
Assistant Director
Oak Ridge National Laboratory
Solid State Division
Oak Ridge, Tennessee

Mr. George C. Deutsch, Chief (1966)
Materials Research Program
National Aeronautics & Space Admin.
Washington, D. C. 20546

Dr. Morris E. Fine (1967)
Associate Chairman
Office of the Chairman
Materials Research Center
Northwestern University
Evanston, Illinois

Dr. Walter L. Finlay (1967)
Assistant to Vice Pres.,—Advanced Technology
Crucible Steel Company of America
4 Gateway Center
Pittsburgh, Pennsylvania

Dr. Wayne E. Hall (1966)
Assistant Chief Geologist
Experimental Geology
U. S. Geological Survey
Washington 25, D. C.

Mr. J. Harry Jackson (1968)
General Director
Metallurgical Research Division
Reynolds Metals Company
Fourth and Canal Streets
Richmond 19, Virginia

Dr. John H. Koenig, Director (1965)
School of Ceramics
College of Engineering
Rutgers University
New Brunswick, New Jersey

Mr. Humboldt W. Leverenz (1968)
Associate Director
RCA Laboratories
David Sarnoff Research Center
Princeton, New Jersey

Mr. Alan Levy (1967)
Manager, Materials & Fabrication
Research and Development Department
Solid Rocket Operations
Aerojet-General Corporation
Sacramento, California

Dr. D. J. McPherson, Director (1967)
Materials and Structures Research
Illinois Institute of Technology
Research Institute
10 West 35th Street
Chicago 16, Illinois

Dr. M. Eugene Merchant (1966)
Director of Physical Research
Cincinnati Milling Machine Company
Cincinnati 9, Ohio

Mr. John M. Neff (1965)
Senior Research Scientist
The Martin Company
MP 275; P. O. Box 5837
Orlando, Florida

Dr. E. F. Osborne (1969)
Vice President for Research
The Pennsylvania State University
University Park, Pennsylvania

Dr. Charles G. Overberger (1965)
Dean of Science
Polytechnic Institute of Brooklyn
333 Jay Street
Brooklyn 1, New York

Dr. Joseph A. Pask (1968)
Department of Mineral Technology
University of California
Berkeley 4, California

Dr. Malcolm M. Renfrew, Head (1967)
Department of Physical Sciences
University of Idaho
Moscow, Idaho

Dr. Preston Robinson (1966)
Director-Consultant
Sprague Electric Company
North Adams, Massachusetts

Mr. J. H. Scaff (1965)
Metallurgical Director
Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey

Dr. Irl C. Schoonover (1966)
Associate Director
National Bureau of Standards
Washington 25, D. C.

Dr. W. H. Steurer (1965)
General Dynamics/Fort Worth
P. O. Box 748, Mail Stop E-63
Fort Worth, Texas 76101

Dean Robert D. Stout (1968)
Graduate School
Lehigh University
Bethlehem, Pennsylvania

Dr. Morris Tanenbaum (1969)
Director of Research and Development
Western Electric Company
P. O. Box 900
Princeton, New Jersey 08540

Mr. Alfred C. Webber (1968)
Research Associate
Plastics Department
Experimental Station
Building 323, Room 210
E. I. duPont de Nemours & Co., Inc.
Wilmington, Delaware 19898

Mr. F. Travers Wood, Jr. (1968)
Deputy Director
Engineering R&D Laboratories
Missile & Space Systems Division
Douglas Aircraft Company, Inc.
Santa Monica, California

MAB-207-M, "MICROMECHANICS OF FIBROUS COMPOSITES"

ERRATA

Page 60, line 11: Read "$\mathcal{G}_{IIc}$"

Page 61, line 1: Read "$\mathcal{G}_{IIc}$"

Page 77, line 5: Read "$\mathcal{G}_{Ic}$"

Page 83, last line: Read "fracture toughness, $\mathcal{G}_c$. That is $\mathcal{G}_I + \mathcal{G}_{II} = \mathcal{G}_c$. This proposal is under"

MAB-207-M

MICROMECHANICS

OF

FIBROUS COMPOSITES

Prepared for

The National Academy of Sciences

by the

MATERIALS ADVISORY BOARD

Division of Engineering and Industrial Research

National Research Council

National Academy of Sciences-National Research Council
Washington, D. C.
May 1965

The Academy and its Research Council perform study, evaluation, or advisory functions through groups composed of individuals selected from academic, governmental, and industrial sources for their competence or interest in the subject under consideration. The members serve as individuals contributing their personal knowledge and judgments and not as representatives of any organization in which they are employed or with which they may be associated.

This report completes a study undertaken by the Materials Advisory Board for the National Academy of Sciences in execution of work under ARPA Contract No. SD-118 between the Department of Defense and the National Academy of Sciences.

MATERIALS ADVISORY BOARD

AD HOC COMMITTEE ON MICROMECHANICS OF FIBROUS COMPOSITES

Chairman: Professor A. G. H. Dietz
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Members

Professor H. T. Corten
Department of Theoretical and Applied Mechanics
College of Engineering
University of Illinois
Urbana, Illinois

Mr. B. Walter Rosen
Space Sciences Laboratory
General Electric Company
P. O. Box 8555
Philadelphia, Pennsylvania 19101

Professor Joseph Gurland
Division of Engineering
Brown University
Providence 12, Rhode Island

Liaison Representatives

Army

Mr. F. W. Schmiedeshoff
Research Branch
Directorate of Research and Engineering
Watervliet Arsenal
Watervliet, New York

Navy

Dr. Harold Liebowitz
Head, Structural Mechanics Branch
Office of Naval Research
Washington 25, D. C.

Air Force

Mr. James M. Whitney
MANC
Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

MAB Staff

Capt. A. M. Blamphin, USN (ret.)
Materials Advisory Board
National Academy of Sciences-
National Research Council
2101 Constitution Avenue, N.W.
Washington, D. C. 20418

Previous page was blank, therefore not filmed.

FOREWORD

The technology of composite materials has been the subject of active attention by the Materials Advisory Board for a number of years. In December 1958, the Board submitted to the Department of Defense its report MAB-146-M on Composite Structural Materials. In January 1962 an MAB ad hoc Task Force provided the DOD with a letter report, MAB-98-LM, on Composite Materials Composed of a Metal Matrix Reinforced with Ceramic Whiskers.

During 1961 and 1962 a special MAB Task Force reviewed composites problems and research activity supported by the DOD and other agencies and made recommendations to the Board concerning particular subjects in which MAB studies in some depth could be helpful to DOD in its efforts to advance composites materials technology. One of these subjects was the micromechanics of fibrous composites, described generally as the internal reactions of the component materials to imposed stress.

The Task Force was aware that in the few highly stressed applications where fibrous composites had been employed (including the filament wound motor cases) the design of the composite had been developed almost entirely by empirical methods, due to the fact that existing knowledge of the interactions of the constituent materials was inadequate to support more rational treatment. Although the composite material parts produced by cut-and-try approaches resulted in worthwhile weight advantage, it could not be demonstrated that optimum structural efficiency or reliability had been achieved.

Thus, although a composite utilizing strong fibers in a suitable matrix offers promise of a structural material with mechanical properties substantially better than those of currently available metals, a sound concept of the ultimate potential of fibrous composites can not be realized until much more is known of the internal reactions. Greater understanding of the mechanics will permit more rational selection of constituent materials properties and geometry and thus facilitate the experimental development of successful composites for many types of high performance applications.

In 1963, the Deputy Director of Defense Research and Engineering requested the National Academy of Sciences-National Research Council to provide an analysis and description of the micromechanics problems in fibrous composites, and to identify areas in which additional research is needed. The study should include an assessment of current knowledge, consideration of the work now supported by DOD and other agencies, and recommendations for strengthening the DOD research effort, theoretical and experimental, leading to better understanding of micromechanics and thence to improved composites technology.

Accordingly, the Academy-Research Council approved the establishment and membership of an _ad hoc_ Committee on the Micromechanics of Fibrous Composites, under the Materials Advisory Board, and this report is the result of that Committee's work. The names of the members are shown on page iii.

At separate times, the DOD requested the Academy-Research Council to conduct two other studies in the composites field, as follows:

Composites. This subject is broad, embracing the general area of composite materials of interest to DOD. The study objective is to identify those problems which limit the development of composite materials required for optimum performance of weapons systems. For this study, the NAS-NRC, in 1963, approved the MAB ad hoc Committee on Composites.

Interfaces. It was recognized that the interfaces in fibrous composites are vital links in the transfer of load between fiber and matrix, and that the lack of understanding of the nature and behavior of interfaces contributes to the difficulties being experienced in developing strong, durable composites. The objective of the study for the DOD is to analyze and describe the interface problems in fibrous composites and identify the needs for additional research. This study, requested in 1962, is being made by the MAB ad hoc Committee on the Interface Problem in Fibrous Composites.

Although these three studies have been conducted by separate committees and are the subjects of separate reports, it is recognized that the problems are interrelated in many aspects. To avoid overlap, or gaps, special effort has been made by each committee to maintain full awareness of the matters considered by the other two and of their conclusions and recommendations. While each report is complete in itself, it is believed that perusal of all three reports will add perspective to the reader's view of the findings of each.

Previous page was blank, therefore not filmed.

CONTENTS

Page

Membership - Ad Hoc Committee on Micromechanics of Fibrous Composites iii

FOREWORD v

ABSTRACT xi

SUMMARY AND RECOMMENDATIONS 1

Summary Conclusions 3

Summary Recommendations 7

INTRODUCTION 9

SCOPE OF THE MICROMECHANICS OF FIBROUS COMPOSITES 15

DISCUSSION 21

1. Definition of Constituent Properties 21

1.3. Recommendations 29

2. Elastic Stress Fields 34

2.1. Typical Elements 34

2.1.3. Recommendations 37

2.2. Average Stress-Strain Behavior 40

2.2.3. Recommendations 42

3. Inelastic Stress Fields 45

3.1. Typical Elements 45

3.2. Average Stress-Strain Behavior 47

3.3. Recommendations 50

CONTENTS

Page

DISCUSSION (Continued)

4. Tensile Failure 53

4.3. Recommendations 64

5. Failure Under Other Loads 68

5.1. Compression 68

5.1.3. Recommendations 73

5.2. Shear and Flexure 75

5.2.3. Recommendations 78

5.3. Multiaxial States of Stress 82

5.3.3. Recommendations 86

5.4. Creep and "Stress Corrosion" 87

5.4.3. Recommendations 89

5.5. Fatigue 92

5.5.3. Recommendations 94

5.6. High Speed Loads 96

5.6.3. Recommendations 97

5.7. Other Environments 98

5.7.3. Recommendation 99

6. Laminates 100

6.3. Recommendations 105

ABSTRACT

When external loads or other stress-inducing forces are applied to a composite of fibers embedded in a matrix, internal stresses are set up in each constituent and at the same time complex interactions occur between them. The study of these internal stresses, the internal mechanics of the reactions of the constituents, separately and in concert, to the imposed forces, may be called the micromechanics of fibrous composites. The reasons for theoretical and experimental research in micromechanics are, (1) to clarify the behavior of fibrous composites and thereby to improve the design of engineering structures based on them, and (2) to improve the properties of composites. In this study, the subject is divided into six areas. Certain aspects of each area are treated with respect to the significance of the area, the state of present knowledge (as available to the Committee), the still unanswered questions, and, to the extent possible, suggested lines of attack for research.

SUMMARY AND RECOMMENDATIONS

Recent demonstrations of the very high strength to density ratios of fibrous composites have focused attention on the potential of these materials. Indeed, fiber reinforced materials have the promise of providing mechanical properties superior to metals for many high performance applications. Fibrous composites offer a new concept of materials, in which it is possible to adapt the material to the design, rather than the design to the material and also to form the composite material as the functional part in one fabrication process. Yet despite this promise, one must recognize the present immature status of composites technology. Composites in use today have been developed largely by empirical methods which, although they have proven useful, have fallen far short of exploiting the full potential of the constituent materials. This document attempts to support the hypothesis that one of the important shortcomings of our present composites technology is the incomplete and inadequate understanding of the micromechanics of such composites; that is, the internal reactions and distribution of stresses among the constituents, under a wide range of types and rates of loading, response to temperature and influences of the environment, and time. In summary, the report emphasizes the great need to foster the application of the principles and approach of continuum mechanics at the scale of the heterogeneous structure of fibrous composites.

This study of micromechanics is presented within the framework of two parallel goals. One is the expectation that the applications of the principles of continuum mechanics, taking into account the mechanical and geometric properties of the constituents, can lead to an understanding of the composite properties which is adequate to quantitatively define the changes in constituent properties necessary to achieve a desired composite performance. Thus, the cooperative efforts of students of solid mechanics and materials science would lead to "tailor-made" composite materials. The other goal is to utilize the understanding of composite materials behavior to enable the achievement of the full potential of the material in structural configurations. Thus, the designer would be provided with the methods to achieve optimum structures designed to utilize advanced fibrous composites.

The Discussion section of the report presents a survey of problems associated with various facets of the micromechanics of fibrous composites including: the definition of constituent and interface properties, the evaluation of elastic and inelastic stress fields for typical idealized geometries; the evaluation of average stress-strain behavior of the composite, the treatment of various composite failure mechanisms, and the study of the mechanics of structural laminates of fibrous composites. In the Discussion section, recommendations for further work are made in connection with each of the major problem areas. The highlights of these are repeated below for emphasis along with a summary of the conclusions associated with each major problem area. In most cases these summary conclusions and recommendations acquire increased clarity and significance when considered in the light of the full statement of the problems as set forth in the Discussion section.

Summary Conclusions

1. Property Definition

Basic mechanical properties of the constituents - fibers, matrix, and interface - need to be determined for the constituents separately and *in situ*, in order to perform any subsequent analyses. The required properties for each constituent include a complete set of independent elastic constants, a definition of properties in the inelastic range, strength properties (statistical where required), geometry definition and treatment of the influence of surface characteristics and thermal effects. The existing body of experimental data is limited and many present experimental techniques are inadequate. Ingenious, often totally new, methods of measurement may be necessary, especially *in situ*.

2. Elastic Stress Fields

Essential to an understanding of the micromechanics of fibrous composites is the basic treatment of idealized geometries of fiber and matrix, starting with single fibers of various shapes and proceeding to multiple fibers at various orientations embedded in a matrix. The stress state of a short fiber embedded in a matrix, including an assessment of the interface problem should be studied. From this follows the next step to actual fibers and matrices, the influence of their imperfections, and the effects of the interface. The stress distribution, in planes normal to the fibers, should be studied to indicate probable modes of failure. Beginnings have been made in this area, but further work, with particular emphasis on multiple element models, is required.

The evaluation of structural behavior requires knowledge of the average stress-strain behavior of the composite. The composite as a whole may be considered utilizing the knowledge of the response of its individual constituents. Although the material is heterogeneous at the microscopic level, the average response may be treated as macroscopically homogeneous. Useful solutions may be obtained by employing variational principles of elastic theory. At this level, materials may be isotropic or anisotropic and the geometry will depart from an ideal distribution of fibers in the matrix. Several initial methods of approach have been proposed. It is necessary to determine experimentally the independent elastic constants of isotropic and anistropic fibrous composites and check them against these theoretically predicted values. It appears that further analytical study is required to assess the influence of fiber distribution, orientation, and volume fractions upon the elastic constants in terms of a statistical representation of the geometry.

3. Inelastic Stress Fields

The same elements that are studied elastically, i.e., fibers, matrix, and interface, need to be studied in the inelastic range so that failure mechanisms can be defined. A beginning should be made with simple systems of single or parallel fibers in a matrix subjected to stresses beyond the elastic range. This should be extended to more complex combinations of fibers and matrices. Time and temperature effects are of greatest importance. It is necessary to study stress-strain-time relations for combinations of elastic fiber and matrix, elastic fiber and inelastic matrix, and inelastic fiber and inelastic matrix, including failure mechanisms. The theoretical analysis should be concerned with the prediction of the stress-strain curve of the composite by considering the flow strengths of the matrix under elastic and inelastic constraint, and by evaluating the stress and strain distribution in the microstructure, both in idealized models and in the actual materials. This entire subject area is relatively unexplored.

4. Tensile Failure

In tension, an important need is a definition of the mode of failure. Theories and studies of failure should be concerned with the uniformity of strain in the constituents at a point, failure of the bond and interface, fiber fracture as a statistical phenomenon, effect of flaws in all constituents, stress concentrations in the interface, single and multiple crack initiation and propagation, fracture toughness and "weakest link" models. Certain of these factors have been included in proposed failure models. However, these are incomplete and experimental observations of the modes of failure in composites are required including crack initiation and propagation, parallel and perpendicular to the fibers under simple tension and multiaxial stress.

5. Failure Under Other Loads

Structures composed of fibrous composites are subjected to stresses other than tensile. These are principally compression, shear, and multiaxial stresses acting simultaneously. Associated with these are the effects of time and rate of loading from static creep to high-speed loading or impact, and of repeated loading fatigue. Environments including high and low temperature and corrosive surroundings may have marked effects upon the behavior of fibrous composites under these various stresses. The required studies are quite broad in scope, and include:

Modes of failure under compression parallel and transverse to fiber directions, buckling, crack initiation, splitting, boundary effects, discontinuity effects, stress transfer and chain reactions leading to failure.

Modes of failure under shear, contributions of fiber, matrix, and interface to shear strength, types and locations of shear cracks, propagation. Effects of discontinuities upon failure initiation.

Modes of failure under combined multiaxial stresses, contribution of each type of stress to composite behavior.

Investigations of and possible interrelationships among static creep, dynamic or high-speed loading, and cyclic loading. Modes of failure, contribution of fiber, matrix, and interface.

Effect of high and low temperatures, moisture, vacuum, and corrosive environments likely to be encountered.

6. Laminates

In some ways these are structures rather than materials, but they involve problems in micromechanics, and an important objective of micromechanics is the most efficient design of laminates. Laminates consist of isotropic and anisotropic layers, complex stresses are set up in the layers, critical shear stresses are set up between layers, and design must be directed toward most efficient and economical use of materials to resist these stresses, both elastic and inelastic, under a wide variety of conditions.

Analyses of internal elastic and inelastic stress distributions and failure mechanisms in and between layers of laminate subjected to simple and combined loads are needed. It is also necessary to evaluate stresses in bond layers between layers of laminate and effects of prestressing and preloading upon performance. These analyses can build upon existing analyses developed in conjunction with plywood technology. Desired analyses leading to optimum arrangements of layers to withstand imposed loads can be facilitated by machine calculations.

Summary Recommendations

The following list of principal recommendations concerns those problems which the Committee feels to be most in need of further study. Detailed recommendations covering these and other areas appear in the Discussion section. In summary, we strongly recommend:

1. A significant expansion of the experimental study of the mechanics of fibrous composites, including:

   a. Techniques for measurement of in situ constituent properties.

   b. Measurement of internal stresses under typical external loads, including residual stress effects.

   c. Development of improved techniques to measure average composite properties.

   d. Observation of failure mechanisms.

2. An assessment of the problem of the mechanics at the interface, including the definition of an analytical model containing a sufficient degree of anisotropy and inhomogeneity to simulate the real materials.

3. Theoretical analyses of the inelastic response of composites, including time effects, for the purpose of defining average stress-strain behavior.

4. Development of a theoretical treatment of failure mechanics for practical loading conditions, with particular emphasis on stresses transverse to the fiber direction.

5. Treatment of structural laminates to evaluate failure mechanisms and optimize configuration.

Previous page was blank, therefore not filmed.

INTRODUCTION

An important class of composite materials and one of rapidly growing application, consists of fibers embedded in a continuous matrix. Many types of fibers and matrices are employed. They all have the common characteristic that the fibers and matrix are bonded together and constrained to act in concert when subjected to external conditions.

When external loads or other stress-inducing forces are applied to a composite of fibers embedded in a matrix, internal stresses are set up in each constituent and at the same time complex interactions occur between them. The study of these internal stresses, the internal mechanics of the reactions of the constituents, separately and in concert, to the imposed forces, may be called the micromechanics of fibrous composites. This report addresses itself to an examination of this subject.

Most importantly, the report attempts to set forth the unanswered questions requiring both theoretical and experimental research to clarify the mechanics of these materials and, consequently, to improve and extend their use.

There are two principal ways in which fibrous reinforcements may behave in fibrous composites. (1) When fibers are short, they act in much the same way as particles and platelets in a continuous matrix, that is, by interfering with deformation of the matrix and thereby markedly increasing the stiffness of the composite. (2) When fibers are long and of high modulus compared with the matrix, loads are carried primarily by the fibers, assisted by the matrix which supports the fibers and transfers stress from fiber to fiber in shear. Because the behavior of straight long fibers in a composite is in itself a highly complex micromechanics problem in need of extensive research, and because the potentialities of such long fiber composites are so great, this report addresses itself principally to this problem. Further, the report does not consider fabrics except as macro-constituents of laminates.

The ultimate reasons for intensive study of micromechanics are two-fold. One reason is to clarify the behavior of fibrous composites and thereby to improve the design of engineering structures based on them. Intimate understanding of the micromechanics of composites will lead not only to the better utilization of the materials but also to the evolution of new structural forms based on the composite's unique properties. As long as the micromechanics of these materials is obscure, optimum design of structures cannot with certainty be achieved, and the capability of best tailoring the properties of the structure to meet the imposed loads will not be realized. By providing insights into theoretical maximum strengths and attainable strengths in the presence of defects (failure theories), predicting optimum fiber concentrations for given design conditions of fiber and matrix properties such as strength, ductility and modulus, micromechanics can provide the tools for the structural analyst to optimize his designs. Intensive analysis and research are needed to explain the many anomalies that now exist in the behavior of these structures. Theory must guide design; experiment must check theory and set limits to it.

The other reason is to improve the properties of composites. Only when there is a quantitative understanding of the effects of matrix, fiber, and interface properties can research and development be intelligently directed toward selecting the proper materials, proportions, and configurations to obtain the optimum properties in the composite. The interactions between constituents are complex and the nature of desired improvements are not obvious without analysis. Indeed, simple "rules" can be quite misleading.

The importance of micromechanics' studies in the development of advanced structural composites is certainly not universally recognized. It is well, perhaps, then to cite some particular examples to indicate the role of mechanics of materials in guiding the fruitful development of structural composites, and thereby to indicate the motivation for this ad hoc study.

A pertinent example is the problem of the micromechanics of the interface region. To be specific, consider a finite length glass fiber embedded in a concentric cylinder of an epoxy matrix subjected to a tensile load parallel to the fiber. To formulate the mechanics problem in its most general form one would include all the possible characteristics of the constituents. Thus, the fiber may well be anisotropic, and be subject to a state of residual stress due to its fabrication process. The matrix, since it is cured in a relatively confined region, may also be anisotropic, may be inelastic, may have properties which vary as a function of the distance from the fiber surface, may have residual stresses, and may be bonded to the fiber in a fashion which permits intermittent slip. Neglect of any of these effects, if they do exist, can result in erroneous conclusions. (For example, it is well known that neglect of the anisotropy of a material like pyrolytic graphite can result in thermal stress solutions which are of the wrong sign as well as being grossly incorrect in magnitude.) However, measurement of all of the above properties in the interface region is an extremely difficult task. A careful micromechanical analysis of the proposed problem could indicate those properties of the matrix, which, if they deviated from the bulk properties, would be most important in their effect on the composite performance. This would provide guidance for the interface investigators in their studies and this could help formulate a discriminating experiment which would enable one to infer matrix characteristics. An understanding of the interface region is most important when one considers failure criteria. Thus, consider the tensile failure of a fibrous composite loaded parallel to the uniaxially oriented fibers. The failure sequence will start with a crack initiation in one phase or the other which will propagate to the adjacent interfaces. Here the interface region characteristics will determine whether the crack: propagates across the interface into the other phase; propagates along the interface thereby separating the two phases; or stops at the interface. The effect of the different matrix and fiber properties upon the state of stress of and strength in the interface region should indicate which of these possibilities is most likely. The nature of improved constituent properties which yield an improved composite is very likely to depend on which of the failure modes is dominant.

Fiber flaws make it not unlikely that a fiber fracture may be the initial internal crack. The possible subsequent failure models include:

1. Crack propagation from this initial fiber break to produce composite failure.
2. Interface separation to yield a bundle of fibers

which then fail as a roving of that length would.

3. Accumulation of distributed fiber breaks to produce a weakened cross-section which then fractures.

The implications of these possibilities point up the need for an analysis which properly explains the failure mode. Thus, if (1) above is the failure mode, the worst flaw will cause composite fracture and the "weakest link" concept would motivate the elimination of this weak link. However, if (3) above is the failure mechanism, a few low-strength flaws are of little concern. In the former case, a high-strength resin and one which can absorb a large amount of strain energy is desirable to resist the crack propagation. In the latter case, the resin must be stiff to localize the effect of each fiber break but only moderate strength is necessary. Note that while all the failure models proposed may explain the macroscopic failure mechanisms of composites, the implications for the desired direction of changes in constituent properties are quite different for the various microscopic mechanical models. In this case, as in many others, only the theoretical and experimental study of micromechanics can rationally indicate the desired change in constituent properties.

For the purposes of this committee study and report, the subject was divided into the following areas:

1. Definition of Constituent Properties
2. Elastic Stress Fields
3. Inelastic Stress Fields
4. Tensile Failure
5. Failure Under Other Loads
6. Laminates

The scope of the subject matter involved in the micromechanics of fibrous composites is portrayed in topical form in a separate section following the Introduction.

In the Discussion section of the report, certain aspects of each area are treated in detail with respect to the significance of the area, the state of present knowledge (as available to the Committee members), the still unanswered questions, and, to the extent possible, suggested lines of attack for research in both theory and experiment which may lead to improved understanding. Also where practical, the relative importance of various areas of research is indicated.

The emphasis throughout is based on the fact that the sequence of events desired for the most profitable influence of materials analysis upon materials development is: first, the development of an analytical understanding, theoretical and experimental, of the relationship between constituent properties (mechanical and geometric) and composite performance; second, the consideration of potential applications, utilizing a parametric study of the effect of material properties upon performance, to define the most desirable constituent properties; and third, the design and development of desirable structural composites guided by the analytical work. Obviously the sequence is an interdisciplinary program with continuous interaction among those involved in materials analysis, development, fabrication, and characterization. The present report is concerned with the requirements for study of the first step indicated above so that the structures community can intelligently perform the second step and provide the desired inputs to the materials community.

References used are intended to be illustrative only and such listing does not constitute a comprehensive bibliography.

SCOPE
OF THE MICROMECHANICS OF FIBROUS COMPOSITES

Listed here are the subject areas considered by the Committee to be of current importance in the study of micromechanics of fibrous composites. The list is incomplete, as would be expected, since it reflects the opinions of a limited group of individuals.

The discussion section of the report treats most of these subjects, although not all, with regard to significance and status and makes recommendations for important future studies. There is not a complete correspondence between the Discussion section and the Scope inasmuch as the Scope listing represents the effort of the Committee to indicate the range of the various aspects of the micromechanics problem, while the Discussion omits those areas which the Committee felt it had neither the time nor the competence to describe.

1. Definition of Constituent Properties

    A. Materials of Interest

        (1) Fibers

            a. Glasses
            b. Ceramics
            c. Metals
            d. Graphite
            e. Organics

        (2) Matrices

            a. Polymers
            b. Metals
            c. Ceramics

        (3) Interface

B. Properties of Interest

(1) Fibers

a. Elastic moduli
b. Tensile strength
c. Inelastic deformation
d. Thermal properties

(2) Matrices

a. Elastic Moduli
b. Constitutive relations
c. Fracture toughness
d. Thermal properties
e. Surface tension and wetting
f. Viscosity
g. Thin film properties

(3) Interface

C. Parameters Which Influence These Properties

(1) Cure

(2) Temperature

(3) Environment (moisture, etc.)

(4) Contact with other phase

(5) In situ properties

D. Experimental Techniques

(See Part B.)

2. Elastic Stress Fields

A. Typical Elements - (Elastic)

(1) Single fiber-cylindrical matrix region of finite or infinite extent

a. Uniaxial tension parallel to fiber
b. Uniaxial compression parallel to fiber
c. Transverse normal loading
d. Shear stress
e. Solutions for variable elastic properties

(2) Two fibers-matrix region of infinite extent

a. Parallel loading
b. Transverse loading
c. Crossed fibers
d. Shear loading
e. Stresses due to a broken fiber

(3) Other considerations

a. Other fiber shapes
b. Finite length fibers
c. Thermal effects

B. Average Stress-Strain Behavior - (Elastic)

(1) Elastic constants of ordered and arbitrary arrays

a. Specified cylindrical geometry for both phases
b. Specified cylindrical fiber shape
c. Arbitrary cylindrical geometry
d. Deviations from idealized geometry
e. Multidirectional fibers
f. Experimental studies

3. Inelastic Stress Fields

A. Typical Elements - (Inelastic)

(1) Single fiber-infinite matrix

a. Buckling
b. Tension loading
c. Normal (transverse loading)
d. Shear loading

(2) Two fibers

a. Parallel loading
b. Normal (transverse) loading
c. Crossed fibers
d. Shear loading

(3) Other considerations applicable to the subjects listed in 2.A and 2.B (single or multiple fibers)

a. Other fiber shapes
b. Finite length fibers
c. Thermal effects
d. Viscous effects
e. Loading rate effect
f. Residual stresses

B. Average Stress-Strain Behavior - (Inelastic)

(1) Consider each type of geometry treated in Part 2 B above

(2) Consider loading which defines each of the elastic constants of the composite

(3) Treat matrix phases which are characterized as

a. Elastic-plastic
b. Visco-elastic

4. Tensile Failure

A. Crack Initiation

(1) Criteria for initial fracture in matrix, fiber or at interface on existing three-dimensional stress field, including effects of adjacent phases

(2) Treatment of brittle and ductile matrix phases

B. Crack Propagation

(1) Single crack

(2) Multiple cracks

(3) Definition of properties and geometry for which single or multiple crack propagation to failure is applicable

(4) Experimental studies

C. Crack arrest

D. Concept to Replace "Weakest Link"

5. Failure Under Other Loads-Definition of Failure Criteria in Conjunction with Experimental Studies

A. Compression

(1) Parallel and normal to fibers

(2) Shear failure of "micro" fibers

(3) Brittle or ductile matrix

(4) Influence of pre-stress

(5) Influence of interface strength on failure mode

B. Shear and Flexure

(1) Parallel or transverse to fibers

(2) Brittle or ductile matrix

(3) Interface effects

C. Multiaxial States of Stress

D. Time-dependent Failure

(1) Creep

(2) Stress corrosion

E. Fatigue

F. High Speed Loads

G. Other Environments

(1) Thermal

(2) Acoustic

6. Laminate Stress Analysis

A. Elastic Behavior

(1) Mechanics of individual layers

a. Isotropic materials, plates
b. Orthotropic materials, plates

(2) Interlaminar stresses

(3) Two-layer laminate

a. Different elastic properties
b. Theory of composite action

(4) Multi-layer laminate

a. Different elastic properties
b. Arbitrary number of layers, thicknesses, directionality
c. Stresses in adhesive layers
d. Cross-elasticity effects

(5) Other effects

a. Dimensional changes, e.g., torsion and twisting
b. Edge effects
c. Plates
d. Shells
e. Instability
f. Materials other than isotropic or orthotropic

B. Inelastic Behavior

(1) Mechanics of individual layers

(2) Interlaminar stresses

(3) Two-layer laminate

(4) Multi-layer laminate

(5) Other effects

a. Relaxation
b. Creep

C. Netting Theory

(1) Basic assumptions

(2) Isotensoid shapes

D. Effects of Imperfections

(1) Variable strength and elastic properties

(2) Variable initial stresses

(3) Variable alignment of elements, e.g., filaments, fabrics

E. Failure Theories

(1) Extension of theories of failure of isotropic materials to laminates

(2) Combined stresses

(3) Brittle failure

(4) Realignment of stresses if individual layers or elements fail

a. Failure in adhesive layers

DISCUSSION

1. Definition of Constituent Properties

1.1. Significance

The properties of the constituent materials themselves exert a determining influence on the properties of the composite. However, to achieve unit structural behavior of a fibrous composite, the constituent materials, i.e., the fibers and matrix, must be compatible at the interface. Interfacial compatibility involves wetting of the fibers by the matrix material (intimate molecular contact) and adhesion between the two materials. If intimate molecular contact of the matrix material with the fibers produces a region of transition between the two bulk materials (or if a layer of coupling agent is introduced) effectively, a third "material" is present between the fiber and matrix bulk materials. Under the action of external loads, temperature changes or gradient, etc., the stresses in each of these materials and the interactions among them depend upon the elastic properties, the inelastic behavior, and fracture characteristics of the three materials. Thus knowledge of the properties of the constituent materials, including an interfacial region, is essential for selection of potentially useful combinations of fiber and matrix materials and for micromechanics analysis of the behavior of constituent materials when combined in composite form.

1.2. Status

1.2.1. Materials of Interest

1.2.1.1. Fibers

Glasses (e.g., E-glass, S-glass, high modulus glass)

Ceramics (e.g., silica, alumina)

Metals (e.g., tungsten, beryllium, boron)

Graphite

Organic fibers (e.g., nylon)

1.2.1.2. Matrices

Polymers

Thermoplastics

Thermosets (e.g., polyesters, epoxies, phenolics)

Elastomers

Metals (e.g., silver, copper, titanium, nickel)

Ceramics

1.2.1.3. Interface

As discussed above, the interface is an anisotropic transition region probably exhibiting a gradation of properties, currently ill-defined.

1.2.2. Properties of Interest

The following list of properties is based primarily upon the minimum needs anticipated for micromechanics analysis.

1.2.2.1. Fibers

Size, shape and geometry (diameter or suitable measure of size and shape of cross-section, length of fiber, cross-sectional size variation along length of fiber, equivalent ℓ/d ratio).

Constitutive Relations

Elastic modulus and Poisson's ratio of isotropic fibers, elastic constants for anisotropic fibers, and for non-homogeneous fibers.

Tensile strength, frequently ultimate tensile strength. (Thin fibers approach maximum attainable tensile strengths thus minimizing yielding.)

Statistical strength distribution.

Strength-length relationship for single and multiple populations (for example, glass fibers exhibit strengths characterized by two distinct severities of flaws (1,2)).

Strength-time to fracture relations in significant environments.

Inelastic deformation characteristics at room and elevated temperature.

Other Thermal Properties

Coefficient of thermal expansion

Thermal conductivity

Specific heat

1.2.2.2. Matrices

Geometry of the matrix as determined by the placement of the fibers

Constitutive Relations (e.g., stress-strain-time-temperature relations)

Fracture Toughness

Other Thermal Properties (expansion, conductivity, specific heat)

Surface Compatibility and Fabrication Characteristics (surface tension and wetting characteristics and viscosity in liquid state)

1.2.2.3. Interface

Constitutive Relations (e.g., stress-strain-time-temperature relations)

Fracture Toughness

Other Thermal Properties

Surface Compatibility and Fabrication Characteristics, if coupling agent

1.2.3. Parameters Which Influence These Properties

Manufacture and fabrication as well as service may have a profound influence upon the properties of the constituent materials. The fabrication process ranges all the way from simple infiltration processes at ambient temperature to the *in situ* formation of a fibrous composite by the directional solidification of the cutectic alloy. The following five areas, denoted here as parameters, indicate the scope of the effects.

1.2.3.1. Matrix Hardening

The cure or hardening of the matrix material particularly if it involves a large temperature change may influence the properties of both the fibers and matrix material.

1.2.3.2. Contact With Other Phases

Contact between two dissimilar phases produces a variety of effects including: possible displacement of adsorbed water and gas layers, changes in the surface energy of the two phases, chemical or physical bonding between the two phases, the introduction of an anisotropic interface layer which provides a continuous transition material between two dissimilar bulk phases, and possible interdiffusion and formation of a layer of alloy of varying composition as a part of the anisotropic interface.

1.2.3.3. In Situ Properties

In addition to items mentioned above, the condition of the fiber surface in situ is important, particularly surface changes which are damaging and result from mechanical or chemical causes. The properties of the matrix between closely packed fibers is significant; specifically, bulk properties of the matrix may be markedly altered in the thin layers and interstitial spaces between fibers. Finally, the manufacture and fabrication of composites currently leaves a gap between the real and idealized continuous multi-phase composite (fibers, matrix, and interface) described above. Real composites usually contain small but significant flaws (foreign matter, misaligned fibers and gas pockets). While unintentional, the effects of flaws cannot be ignored in analysis of failure mechanisms particularly crack extension.

1.2.3.4. Temperature

Temperature is a parameter of manufacture and fabrication and also of service. All mechanical and thermal properties listed in 1.2.2, Properties of Interest, are fuctions of temperature. Also residual stresses are developed during temperature changes due to differential thermal expansion and contraction. Creep and viscoelastic deformations are highly temperature dependent. Nearly all chemical changes, melting, resin curing, diffusion, bonding, corrosion, and decomposition also are highly temperature dependent.

1.2.3.5. Environment

Moisture and other gases in the form of vapor and adsorbed surface layers influence both fabrication processes and service performance. In service, radiation effects and chemical action may contribute to degradation of a composite. These effects influence both the properties of the constituent materials *in situ* and the configuration of the composite, primarily by causing weak interfacial layers or even separation between fibers and matrix.

1.2.4. Experimental Measurements

Typical examples of the types of measurements that have been made are cited.

1.2.4.1. Reinforcement

The longitudinal modulus of elasticity of fibers has been measured indirectly based on tensile load-elongation data for strands or rings (3) and by measuring the velocity of elastic longitudinal wave propagation in single fibers (4). For crystalline filaments and whiskers, longitudinal modulus must be correlated with the crystal orientation and crystal geometry (5,6). Strength measurements of glass fibers loaded in axial tension have been made to study (a) the strength of birgin fibers (7,28), (b) the strength distribution of damaged fibers (2,8), (c) the length-strength size effect relation (1,2), (d) the influence of temperature when the test is conducted at temperature (4), and (e) when the test is conducted at room temperature following heating (7,9,28). Also the influence of a variety of environments upon the strength of glass fibers has been studied (10,11,28).

Similar studies have been made on metal, intermetallic compound and ceramics fibers (12,6,5,13). With metal fibers, one of the in situ problems is the tendency of many combinations of matrix material to alloy with the fibers. This phenomenon may produce a finite thickness interface layer and may have a very deleterious effect upon the strength of the fibers (12). Many of these studies have attempted to isolate one or several of the factors known to affect the properties, particularly strength of fibers in situ. In general, these studies indicate that several important effects exist; however, much remains to be done before the micromechanics problems can be defined in terms of the properties of the fibers, including the influence of the interface on specific properties.

1.2.4.2. Matrix

Studies of matrix materials frequently include conventional measurements of mechanical properties of bulk materials and measurement of composite properties employing the particular matrix material (13,14, 15,16,17,18,27,29).

Several instances can be cited where good agreement between predicted and observed behavior of composites based on bulk matrix properties was observed (13,27,30,31); however, frequently the opposite has been observed (13,14,18,29). Presumably the lack of correlation is attributable either to measurement of bulk matrix properties that are not determining to composite performance or because other features of the composite, namely the reinforcement or the reinforcement-matrix interaction, dominate the composite performance (18,29).

Properties in situ remain relatively unknown partially because of the small size involved but also because of the influence of neighboring phases upon the structure and therefore the properties of thin sections. In most studies it is commonly assumed that the bulk properties bear some qualitative relation to the properties in situ. Undoubtedly bulk and in situ properties are related in some fashion; however, at this time this relation is unknown and it appears that the relation is not constant but dependent on the constituent materials. It is obvious that ingenious techniques are required to measure the properties of the constituent materials in situ in order to undertake the additional tasks of micromechanics listed in later sections of this report. In like manner, consideration of the tasks of micromechanics may well suggest suitable approaches to measurement of in situ properties.

1.2.4.3. Interface Region

The interface region has been treated as one of the constituent materials primarily to emphasize its importance. However, it is difficult to adequately define or isolate the interface for study. Several studies have been made to measure the strength of the interface, that is, the bond between the fibers and matrix (20,21). Such studies are complicated by the presence of residual stresses caused primarily by the larger thermal contraction of the matrix resin as compared with the glass fibers. Depending upon the fiber configuration, the residual stresses may be radial compression which aids bonding (20,21) or radial tension which acts to separate the bond (22), or both Thus micromechanics analysis must be employed to separate the influence of residual stresses from the true bond strength.

With glass fiber-epoxy composites, photoelasticity can be employed to advantage to confirm several aspects of the residual stress analysis (26). In instances when fabrication results in high residual stresses, the evidence indicates that either the resin matrix or the bond, or both, fractured prior to loading or at low values of load (21). These factors all contribute to the complexity of the problem, and illustrate the interdependence of constituent property determination and micromechanics analysis.

Recent studies of the strength of the interface layer have employed somewhat simpler geometry and recognized the importance of flaws or debonded regions (19,23,24,25). In the presence of flaws and debonded regions, the strength of the interface layer is controlled by extension of these flaws and debonded regions. The resulting cracks may be treated in terms of linear elastic fracture mechanics and the fracture toughness of the interface layer (23,24). This approach promises a definitive measurement of bond strength complicated to a much smaller degree by associated but extraneous variables such as residual stresses.

1.3. Recommendations

For micromechanics analyses, study, and predictions, required property measurements are:

1.3.1. Fibers

1.3.1.1. Adequate description of the geometry of the fibers.

1.3.1.2. Constitutive Relations

1.3.1.2.1. Elastic constants, i.e., longitudinal and transverse moduli and Poisson's ratios.

1.3.1.2.2. Tensile strength-time-temperature relation including scatter in strength, length-strength relation, and the influence of environment upon strength.

1.3.1.2.3. Inelastic deformation-time-temperature behavior

1.3.1.3. Other thermal properties (expansion, conductivity and specific heat).

1.3.2. Matrices (including coupling agents).

1.3.2.1. Constitutive Relations (stress-strain-time-temperature relations) for bulk materials and for thin films in contact with fibers as a function of the proximity of the fiber surface.

1.3.2.2. Fracture toughness as a function of proximity to fiber surface.

1.3.2.3. Other thermal properties.

Measurement of properties _in situ_ must be viewed as a challenge worthy of major effort and ingenuity. Unique approaches and methods certainly are required to perform definitive measurements, i.e., to separate the effects of geometry and residual stresses from the property itself.

1.4. References

1. Kies, J. A., "The Strength of Glass," NRL Report 5098, 3 Apr 1958.

2. Metcalfe, A. G. and Schmitz, G. K., "Effect of Length on the Strength of Glass Fibers," ASTM Preprint 87, 1964.

3. Peterson, G. P., "Engineering Properties of High Modulus Reinforced Plastics," Section 1a, 17th Annual Conference of Reinforced Plastics Division, SPI, Feb. 1962.

4. Otto, W. H., "Properties of Glass Fibers at Elevated Temperature," Final Report, Owens-Corning Fiberglas Corp. to U.S. Navy, Bureau of Aeronautics, Contract NOas-58-841-c, Aug. 1959.

5. Gatti, A., Cree, R., Feingold, E. and Mehan, R., "The Synthesis of Boron Carbide Filaments," Final Report Space Sciences Lab., Missile and Space Div., G.E. Co., July 10, 1964, for NASA, Contract NASw-670.

6. Brenner, S. S., "Properties of Whiskers in Growth and Perfection of Crystals," J. Wiley and Sons, 1958.

7. Thomas, W. F., "The Strength and Properties of Glass Fibres," Physics and Chemistry of Glasses, Vol. 1, No. 1, Feb. 1960.

8. Wallhaus, R. A., "A Statistical Study of Factors Influencing the Strength of Glass Fibers," TAM Report No. 217, Univ. of Illinois, May 1962 for U.S. Naval Res. Lab. Contract Nonr 2947(02)(X). AD-276494. Available from OTS, U.S. Dept. of Commerce, Washington, D.C.

9. Cameron, N. M., "The Effect of Annealing on the Room Temperature Strength of Glass Fibers," TAM Report No. 207, Jan. 1962, Univ. of Illinois, for U.S. Naval Res. Lab., Contract Nonr 2947 (02)(X).

10. Duft, B., Dharmarajan, S., and Otto, W. H., "Interaction Mechanism Between Binder and Reinforcing Fibers in a Filament Wound Composite," Narmco R&D, Glass Filament R&D Conference, Lockheed Missiles & Space Co. Facility, Palo Alto, Calif., Jan. 1962.

11. Jordon, T. J., Hollinger, D. L., and Plant, H. T., "High Strength Glass Fibers Development Program," Final Report, Flight Propulsion Lab. Dept., General Electric Co., Evendale, Ohio, Contract NOw-61-0641-c, May 1962.

12. Petrasek, D. W. and Weeton, J. W., "Alloying Effects on Tungsten-Fiber-Reinforced Copper Alloy or High-Temperature-Alloy Matrix Composites," NASA TN D-1568, October 1963.

1.4. References (Continued)

13. Sutton, W. H., Gatti, A., Brenner, S.S., Feingold, E., Chorne, J., Talento, A., Hess, I., Schmidt, F. J., Dow, N. F., and Regester, R., "Development of Composite Structural Materials for High Temperature Applications," Space Sciences Lab., Missile and Space Vehicle Dept., General Electric Co., for U.S. Navy BuWeps, Contract NOw-60-0465-d, Progress Reports 1-17, 1960-1964.

14. Loveless, H. S., "Study of Toughness of Polyester Resins: A Utility Index for Resins Used in Glass-Reinforced Plastics Laminates," Proc. SPI, 16th Annual Reinforced Plastics Conference, Section 13F, Feb. 1961.

15. Brookfield, K. J. and Pickthall, D., "Some Further Studies on the Effect of Glass-Resin Type and Cure on the Strength of Laminates," Proc. SPI, 17th Annual Reinforced Plastics Conf., Section 10A, Feb. 1962.

16. "Research on Improved Epoxy Resins," Union Carbide Corp., Plastics Div. Quarterly Progress Report No. 6, Oct. 1, 1964, Contract No. Nonr-4172(00)(X) for the U.S. Naval Res. Lab.

17. Griffith, J. R. and Whisenhunt, Jr., F.S., "Filament-Winding Plastics, Part I - Molecular Structure and Tensile Properties," NRL Report 6047, March 16, 1964.

18. "Development of Improved Resin Systems for Filament-Wound Structures," Aerojet-General Corp. Report 0626-VI-F, Aug. 1964, Contract NOw-63-0627c(FBM).

19. Bascom, W. D., "Some Surface Chemical Aspects of Glass-Resin Composites, Part I - Wetting Behavior of Epoxy Resins on Glass Filaments," NRL Report 6140, Aug. 10, 1964.

20. McGarry, F. J., "Resin-Glass Bond Characteristics," ASTM Bulletin, 63, Jan. 1959.

21. Broutman, L. J. and McGarry, F. J., "Glass-Resin Joint Strength Studies," Proc. SPI, 17th Annual Reinforced Plastics Conference, Section 1G, Feb. 1962.

22. West, D. C. and Outwater, J. O., "The Stress Distribution in the Resin of Reinforced Plastics," Proc. SPI, 16th Annual Reinforced Plastics Conference, Section 19B, Feb. 1961.

1.4. References (Continued)

23. Ripling, E. J., Mostovoy, S., and Patrick, R. L., "Application of Fracture Mechanics to Adhesive Joints," Symposium on Recent Development in Adhesion Science," Special Tech. Publication No. 360, ASTM, 1963.

24. Ripling, E. J., Mostovoy, S., and Patrick, R. L., "Measuring Fracture Toughness of Adhesive Joints," Materials Research and Standards, ASTM, March 1964, pp 129-134.

25. McGarry, F. J., "Fracture Surface Work of Modified Polyesters and Certain Crosslinked Polyesters," Res. Report R-63-46, Dept. of Civil Engrg., Materials Res. Lab., M.I.T., Sept. 1963.

26. McGarry, F. J., "Fiber Resin Interaction-I MCA-MIT Plastics Research Project," Progress Report, Plastics Res. Lab., M.I.T., July 15, 1961.

27. Rosen, B. W., "Mechanics of Composite Strengthening," Report No. R64SD80, Space Sciences Lab., General Electric Co., Presented at ASM Seminar on Fiber Composite Materials, Philadelphia, Pennsylvania, Oct. 1964.

28. Cameron, N. M., "An Investigation into the Effects of Environmental Treatments on the Strength of E-Glass Fibers," (Ph.D. Thesis), TAM Report No. 274, Jan. 1965, on BuWeps Contracts No-w 64-0p78-d and No-w 65-0204-d.

29. Whisenhunt, Jr., F. S., "Filament-Winding Plastics, Part 2 - Role of the Resin in Glass-Fiber-Reinforced Structures Under Tensile Stress," Naval Res. Lab. Report No. 6161, Dec. 1, 1964.

30. Melvin, J. W., "Effect of Resin Properties on the Fracture of FRP Laminate Models," TAM Report No. 249, July 1963, for U.S. Naval Research Lab., Contract Nonr (02)(X).

31. Melvin, J. W., "Theoretical and Experimental Investigation of the Tensile Moduli of Parallel Filament Composites," TAM Report No. 271, Oct. 1964, for Bureau of Naval Weapons, Contract NO-w64-0178-d.

2. Elastic Stress Fields

2.1. Typical Elements (Elastic)

2.1.1. Significance

One of the fundamental areas of micromechanics studies is the consideration of elastic stresses in elements of idealized geometry subjected to simple states of stress. These basic studies of the interactions between the constituents of a composite material serve several functions. First, they are the building blocks which contribute to the evaluations of average elastic response of realistic composites of more complex geometry. Secondly, the definition of the various stress components contributes to the determination of the failure mechanisms. For brittle constituents, these elastic solutions can be used directly in definition of failure criteria. For inelastic constituents, these solutions provide guidance in the selection of the appropriate problems. Further, as indicated in the previous discussion of micromechanics of the interface, these solutions can provide guidance in the selection of experimental approaches for property measurements.

2.1.2. Status

The existing literature contains work on the elastic stress fields for one and two circular fibers subjected to particular states of stress.

2.1.2.1. Single Fiber

For a single circular fiber in a concentric circular matrix which is finite or infinite in extent, the solution for a uniform axial end displacement of fiber and matrix is readily obtained. However, when the boundary condition is one of uniform uniaxial traction, the solution in the vicinity of fiber ends is the difficult "end problem." Away from the fiber ends an appropriately selected uniform displacement solution is applicable. The end problem has been studied using approximate stress functions (1), and a numerical solution to this particular fiber problem appears reasonable. When the uniaxial load is compressive, the possibility of an elastic instability failure mode exists. This has been treated approximately in the fashion of a column on an elastic foundation (2). It may also be possible to consider a distributed interior line load to improve this result. When the fiber is of finite length within the matrix, it is possible to obtain a solution for an approximation of the end geometry (3).

When the matrix containing a single fiber is subjected to stresses normal to the fiber direction, the stress solution for an isotropic stress state (4) or a state of pure shear (5) applied on the cylindrical boundaries of the composite exist for the case of continuity of displacements across the interface.

Further study is required to evaluate the stress solution for pure applied shear in a fiber plane. Further, a solution for a variety of applied stress states is desired for the case of variable elastic properties with rotational symmetry of the variation. This would be useful as an initial capability to evaluate stresses in the interface region and also the effects of interface properties under the assumption that the interface would eventually be defined in a suitable fashion.

2.1.2.2. Two Fibers

For loading parallel to the fibers, when the fibers are sufficiently close that their radial stress fields interact, an approximate numerical solution may be feasible. When the two fibers are aligned end to end, as in the case of a broken fiber, approximations exist based on approximations in the elasticity equations (6) or in the fiber geometry (3). When one discontinuous fiber is adjacent to one or more continuous fibers, the stresses in the vicinity of the fiber break have been evaluated for two dimensional stress states (7,8).

For transverse states of applied stress with inclusions close together, it may be possible to obtain a solution. When the inclusions are sufficiently far apart in a large matrix, the solutions for multiple fibers are obtained by superposition of single fiber solutions.

Important unsolved problem areas in this general subject area involve the treatment of crossed fibers subjected to normal loading and parallel fibers subjected to parallel shear loads. These states of stress occur in filament wound structures and the modes of failure are not well understood. The elastic solution may provide insight into the possible failure mechanisms. A major unresolved problem is that of stresses in the vicinity of a fiber break. Lack of experimental work in this area is the principal shortcoming and is needed in addition to further theoretical study including the effects of adjacent fibers, parallel or crossed, and variable material properties.

2.1.2.3. Other Problem Areas

Consideration should be given to fiber shapes other than solid and hollow circular ones. Ribbons or elliptical fibers may substantially enhance transverse strength and stiffness. Triangular or hexagonal filaments may increase packing densities and diminish shear stresses.

Thermal effects must be considered. Residual stress states due to the fabrication process can be evaluated for single fibers when a solution to the end problem is available. Solutions for multiple close fibers are required as well as a study of the effects of thermal gradients, their effect on properties, and on the residual stress state.

The effect of the nature of the interface bond can be explored by treating approximate conditions simulating slip and intermittent bonding.

2.1.3. Recommendations

The desirable idealized problems are those which can provide insight into the over-all behavior of the composite. Two significant composite problem areas which can benefit from such treatment are: one, the evaluation of interface stresses, and two, the failure mechanisms for biaxial laminates subjected to in-plane loads. For the former it is of interest to establish a model which contains many of the possible variations of properties which might exist in the interface region. An analysis of this model for the possible degrees of anisotropy and inhomogeneity which might exist would indicate which effects are important and should therefore be studied in detail, experimentally as well as analytically.

When fibers are used in more than one direction, the problem of shear failure mechanisms is most important. Thus, idealizations of the problems of shear stresses in planes parallel and normal to one or two fibers in a homogeneous matrix are desired. Recommended typical stress problems are, therefore:

2.1.3.1. Consider the stress state of a short fiber imbedded in a suitable matrix to aid in assessing the interface problem. (E.g., the matrix may be considered to be orthotropic with elastic properties varying in the radial direction.)

2.1.3.2. Consider stress distributions which may indicate the mode of failure for laminate shear stresses. (E.g., pure shear applied in a plane containing the fiber axis or the influence of an adjacent fiber on the stress field for pure shear in a plane transverse to the fibers.)

2.1.4. References

1. Horvay, G. and Mirabal, J.A., "The End Problem of Cylinders," Journal of Applied Mechanics, Dec. 1958.

2. Dow, N. F. and Gruntfest, I. J., "Determination of Most Needed Potentially Possible Improvements in Materials for Ballistic and Space Vehicles," General Electric Company, Space Sciences Laboratory, TIS R60SD389, June 1960.

3. Sadowsky, M. I., "Transfer of Force by High Strength Flakes in a Composite Material," Watervliet Arsenal, WVT-RR-6105-R, June 1961.

4. Goodier, J. N., "Concentration of Stress Around Spherical and Cylindrical Inclusions and Flaws," Journal of Applied Mechanics, Trans. ASME, Vol. 55, 1933, pp. A39-44.

5. Hashin, Z. and Rosen, B. W., "The Elastic Moduli of Fiber Reinforced Materials," J. Applied Mechanics, June 1964.

6. Dow, N. F., "Study of Stresses Near a Discontinuity in a Filament-Reinforced Composite Material," General Electric Co., Space Sciences Laboratory, Space Mechanics Memo 102, Jan. 1961.

7. Sadowsky, M. A., "Effect of Poisson's Ratio of an Elastic Filler on Force Transfer Between Embeddedded Microfibers," Watervliet Arsenal, SVT-RR-6108-R, September 1961.

8. Hedgepeth, J. M., "Stress Concentrations in Filamentary Structures," NASA TN-D-882, May 1961.

2.2. Average Stress-Strain Behavior (Elastic)

2.2.1. Significance

The use of high strength materials leads to the reduction in material thickness and aggravates the problems of structural deflections and, for compression, structural stability. For many aerospace applications, these problems are of overriding importance and the elastic deformation of fibrous composites is a significant study area.

2.2.2. Status

The concept of an average stress-strain curve is based on the concept that in many cases it is reasonable that a composite can be considered as a statistically homogeneous body subjected to applied stresses and that the average stress or strain over a dimension large compared to any inhomogeneity is the response of interest. The direct approach to the evaluation of effective elastic constants is then to determine the exact state of stress and strain in the non-homogeneous material and to compute appropriate averages. Although obtaining the exact solutions is generally hopelessly impractical, approximate solutions for idealized geometries can be utilized (for example 1,2,3).

An alternate approach is to make use of the variational principles of the theory of elasticity to bound the strain energy and through this approach to obtain bounds on the elastic constants. This approach avoids the uncertainty of using an approximation of unknown accuracy, but does have the problem that the distance between the bounds may be large for constituents of widely differing elastic constants. A recent survey of the status of the mechanics of heterogeneous materials

(4) includes a substantial description of the problem of elastic constants of fibrous composites. Exact bounds for isotropic composites of arbitrary phase geometry have been obtained (5,6,7,8). These have led to the definition of the best possible bounds on the bulk modulus based on constituent properties and volume fractions alone. Any better bounds would require a definition of geometry, probably in the form of a statistical characterization of the material.

For a uniaxially stiffened matrix, the composite is anisotropic. For random geometry in the transverse plane, the material may be considered to be transversely isotropic. The five elastic constants for such an array have been bounded (9) exactly for particular geometries with expressions which can be applied in general by making a geometric approximation. Bounds for arbitrary transverse section geometry have also been obtained (11,12), without any approximation. The uniaxial results can generally be directly applied to ordered arrays of fibers, such as filament wound laminates, to obtain elastic constants as well as average internal stresses, in each lamina for any arbitrary externally applied stresses or deformations.

The problem areas here include the treatment of geometric variations from the ideal. Effects of fiber misalignment, geometry variation in the longitudinal direction and discontinuous fibers must all be considered. Also in an effort to decrease the distance between existing bounds statistical description of geometry must be obtained in a fashion suitable for use in the elasticity analyses.

It is not clear what type of statistical geometry definition can be so used. One approach to this would be to use statistical measures of fiber spacing in a strain energy bounding technique. Another possibility is to define the n-point correlation coefficients for a material. An attempt to incorporate a measure of fiber contiguity in the elastic constant definition has already been made (10).

Another aspect of the study of heterogeneous materials is contained in (13).

The assessment of the merits of these various theoretical approaches is assisted by the examination of experimental data. Presently, data on the elastic constants of fibrous composites are extremely scarce. There is a strong need for measurements of all the independent elastic constants. Techniques for doing this (10) are in need of standardization. Correlation of results with statistical geometric characterization is also desirable. The importance of elastic constants other than the Young's modulus in the fiber direction is certainly inadequately represented by the amount of available data.

2.2.3. Recommendations

Analytically, the status of this subject area is in reasonably good state. Various bounding procedures for all of the independent elastic constants of a fibrous composite have been rigorously derived. To proceed beyond this, some statistical characterization of the transverse plane phase geometry appears to be required so that the location of an elastic constant within the bounds may be determined. Also, it has been shown (12) that certain of the constants are uniquely related as a function of phase properties. Further relations of this type may exist and some study of this may be warranted. Additionally, the status of experimental measurements of elastic properties is not well advanced. Neither the experimental methods nor exact values for composites of interest have been studied extensively. Accordingly, the principal recommendations of typical problems in this area are as follows:

2.2.3.1. Obtain experimental data on all the independent elastic constants of appropriate uniaxially oriented fibrous composites and standardize the techniques for doing this.

2.2.3.2. Study the influence of fiber distribution, for a given orientation and volume fraction, upon elastic constants and explore statistical techniques for this evaluation.

2.2.4. References

1. Outwater, J. O., Jr., "The Mechanics of Plastics Reinforcement in Tension," Modern Plastics, 1956, p. 156.

2. Sonneborn, R. H., "Fiberglass Reinforced Plastics," Reinhold, New York, N.Y., 1954.

3. Shaffer, B. W., "Stress-Strain Relations of Reinforced Plastics Parallel and Normal to Their Internal Filaments," AIAA Journal, February 1964.

4. Hashin, Z., "Theory of Mechanical Behavior of Heterogeneous Media," Applied Mechanics Reviews, 1964.

5. Paul, B., "Prediction of Elastic Constants of Multiphase Materials," Trans. AIME, Vol. 219, February 1960, pp. 36-41.

6. Hashin, Z., "The Elastic Moduli of Heterogeneous Materials," J. Applied Mechanics, Vol. 29, Trans. ASME, Vol. 84, 1962, pp. 143-150.

7. Hashin, Z. and Shtrikman, S., "A Variational Approach to the Theory of the Elastic Behavior of Multiphase Materials," J. Mechanics and Physics of Solids, Vol. II, 1963, pp. 126-140.

8. Hill, R., "Elastic Properties of Reinforced Solids: Some Theoretical Principles," J. Mech. Phys. Solids, Vol. II, p. 357, 1963.

9. Hashin, Z., and Rosen, B. W., "The Elastic Moduli of Fiber Reinforced Materials," J. Applied Mechanics, June 1964.

10. Tsai, S., "Structural Behavior of Composite Materials," NASA CR-71, July 1964.

11. Hashin, Z., "On Elastic Behavior of Fiber Reinforced Materials of Arbitrary Transverse Phase Geometry," to be published in J. Mech. Phys. Solids, 1965.

12. Hill, R., "Theory of Mechanical Properties of Fiber-Strengthened Materials: I Elastic Behavior," J. Mech. Phys. Solids, 1964, Vol. 12, pp. 199-212.

13. Mindlin, R. D., "Microstructure in Linear Elasticity," ONR Contract Nonr 266(09), Columbia Univ., Oct. 1963.

3. Inelastic Stress Fields

3.1. Typical Elements

3.1.1. Significance

The significance of the consideration of typical elements is the same here as in Section 2.1. The typical elements constitute the building blocks of the complex structure, and an understanding of these simple models is a prerequisite to understanding the aggregate.

3.1.2. Status

The simplest element consists of a circular fiber in a concentric circular matrix, and the theory of its mechanical behavior is available for conditions of axial loading. The corresponding analysis is based upon a simple system consisting of two parallel bars, one of fiber material, the other of matrix material, joined to rigid end-plates, i.e., restricted to equal strai the parallel bars. The load is a single force parallel to the bars, and, if end effects and lateral interactions are ignored, the internal stresses are obtainable from equilibrium equations and compatibility conditions for all idealized linear or non-linear combinations of materials. Taking the .teral interaction into account, the model of concentric circular cylinders is also used to describe the behavior in torsion and compression. In the latter case, a difficult problem of practical importance is that of fiber buckling in elastic and viscoelastic media (1).

If unequal permanent deformation of the bars takes place during loading, subsequent unloading will result in residual stresses, which can be evaluated. Complete discussion of the internal deformation is found in papers concerned with structures under general variable loading (2), and shake-down theorems, although these are most often limited to materials which exhibit ideal plasticity or linear strain hardening.

The elastic-plastic analysis of residual temperature stresses is also based on models of concentric cylinders. Plane strain solutions are available for the expansion of a plastic cylindrical tube due to internal pressure (3), but, in many cases, detailed knowledge is lacking concerning the variation of elastic and plastic properties with temperature. The effect of viscous flow during anneal of a composite visco-elastic cylinder is discussed in the literature (4); also, the thermal stresses in cylinders of viscoelastic materials under the influence of a radial temperature distribution can be calculated (5).

The model breaks down if one considers transverse loading, when stress distribution and concentration effects occur at the fiber-matrix interface, which may cause local yielding (6). To our knowledge, the problem of plastic yielding at or between inclusions has not been solved, although problems dealing with other kinds of discontinuities, such as holes and cracks, have been described. Some useful information may also be derived from the solutions of problems involving a rough boundary between rigid and plastic materials, such as indentation, piercing, and compression between rough plates. Clearly, this is an important area of theoretical research which will be further discussed in the next section.

3.2. Average Stress-Strain Behavior (Inelastic)

3.2.1. Significance

Understanding of the behavior in the inelastic range is required for composites, particularly metal-base, which may enter this range during fabrication, shake-down procedures, and high overloads during use. Also from another point of view, namely that of ultimate strength, the possibility of local elongation of the resin or of local plasticity of the metal is very important, since these effects exert considerable influence on the ease of crack propagation and hence on failure strength.

3.2.2. Status

In practically all cases the stress-strain curve is not linear up to failure. Glass-reinforced plastics show permanent deformation of the order of magnitude of elastic strains, whereas in metal fiber-reinforced metals the elongation at failure reaches 10-20%. The stress-strain behavior is logically divided into four stages (7):

1. Elastic deformation of both fibers and matrix.
2. Inelastic deformation of matrix, but elastic deformation of the fibers.
3. Inelastic deformation of both fibers and matrix.
4. Failure of fibers, resulting in failure of composite.

The proportional limit constitutes the boundary between stages 1 and 2. It has not been established that the proportional limit is increased by the presence of the rigid fibers. In the case of metal matrices, it has been shown (7,8) that the deviation from linear proportionality is associated with the onset of plastic deformation in the matrix.

Stage 2 is often linear if the composite is loaded in the direction of the fiber reinforcement, both in resins and metals. The slope is then proportional to fiber concentration. The linear behavior corresponds to the simple model discussed previously as a typical element (6). More generally, a "mixture rule" allows an estimation of flow stress at any value of strain at all stages of deformation (7),

$$\sigma_c^* = \sigma_f^* A_f + \sigma_m^* A_m$$

where the A's are volume fractions, and the starred σ's represent stresses at that particular value of strain for the conditions in which fiber and matrix exist in the composite. The uniaxial extension is discussed in some detail by Hill (11), with particular attention to composites with elastic-plastic matrices.

If the composite is not loaded in the axial direction of the fibers, or if the fibers are not continuous or not all parallel, but, for instance, randomly oriented, the simple model is not applicable. In addition to carrying part of the load, the matrix transmits the load stresses to the fibers. Approximate analyses of the resulting nonlinear stress-strain curves are based on specific geometric arrangements and highly idealized models, which in many cases are not realistic. The problem here is the same as that for the analysis of other composite materials, such as particle reinforced - and dispersion-hardened metals, in that little is known about the plastic behavior of the matrix in the region of constrained plasticity.

For fiber-reinforced metals, a beginning has been made by Koppenaal and Parikh (8) who propose a hardening mechanism analogous to grain boundary strengthening, which is based on dislocation pile-ups at the metal-fiber interface. Reference should also be made to related metallurgical work on the strengthening of ductile layers between rigid plates as found in brazed and soldered joints (9), and to many papers on particle strengthening.

The difficulty with resin matrix composites is that the cause of the nonlinearity of the stress-strain curve is not always understood. It may be due to the elongation of the resin, but, in several cases, it has been shown to be caused by localized cracking in the resin, or of the glass filaments, or by debonding at the fiber-resin interface. Before the behavior of composites can be analyzed successfully, much more must be known about the mechanism of inelastic deformation of resins, and, in general, about the relations between mechanical properties and microscopic structure or chemical constitution.

Complementary studies from the continuum point of view are almost completely lacking. In a recent paper, Drucker (10) applies plastic limit analysis concepts to multi-phase aggregates and predicts the behavior of specific types of particle reinforced metals. He attempts to demonstrate that microstructures are analogous in their behavior under stress to engineering structures under load. As far as is known, this type of analysis has not yet been applied to fiber composites.

The theory of mechanical behavior can be approached on two levels: one, dislocations and crystal defects in metals, or molecular phenomena in plastics, and two, macroscopic, i.e., mechanics of solids. It is believed that it is the latter which will be most immediately useful for the engineering design of materials, because of its generality, and of its predictive aspects, when applied to the mechanics of aggregates of microscopic constituents. Of course, for the purpose of obtaining complete control of the mechanical behavior, understanding of the former level is a necessary requirement and must eventually be achieved. It can probably be stated as an accepted fact that the development of theoretical analysis in this area of micromechanics is severely limited by the lack of appropriate experimental data, against which the theoretical predictions could be checked. It is generally insufficient to compare the stress-strain curve of a material with that of a particular model, and additional independent evidence is required to uniquely describe the mechanism of deformation. This calls for painstaking work on the microscopic level.

3.3. Recommendations

3.3.1.1. Experimental study of stress-strain behavior in the inelastic range of simple fiber-matrix systems, systematically varied as to orientation, length, size, spacing, and characteristic properties of the fibers.

3.3.1.2. The study of the macroscopic behavior should be supplemented by examination and analysis of localized effects of stress distribution and failure. An important problem is the stress distribution around a broken fibar and in neighboring unbroken fibers when the matrix exhibits localized plastic deformation. Another class of problems involves an elastic fiber, an elastic matrix, and an elastic-plastic interface layer. Under these conditions the boundary of the elastic-plastic region is assumed to be known and the usual difficulty of locating this boundary is not present. The solution of this last problem would have immediate practical application in terms of the influence of a low yield strength plastic interface layer.

3.3.1.3. Possible experimental techniques: microscopic examination of slip, deformation, and cracking at all stages of the stress-strain curve; x-ray stress measurements on crystalline constituents; photoelastic study of models; microphotoelastic analysis of stress fields around inclusions; internal friction, hysteresis, and elastic modulus measurements.

3.3.2. Application of theories of continuum mechanics of solids to calculation of:

3.3.2.1. Flow strength of matrix under elastic, viscoelastic, and plastic multi-axial constraint.

3.3.2.2. Stress and strain distribution in microstructure of composite as function of fiber orientation and characteristics.

3.3.2.3. Stress-strain curves by application of macroscopic theories to the combined action of the structural components.

3.3.3. Characterization of the mechanical behavior of matrix materials in the inelastic region from the point of view of the interactions of heterogeneities and micromechanisms of deformation. Specifically, this will require continued study of the molecular theories of rheological behavior and extension of dislocation theories to include the effects of heterogeneities in metals.

3.4. References

1. Biot, M. A., "Continuum Theory of Stability of an Embedded Layer in Finite Elasticity under Initial Stress," Quart. J. Mech. and Applied Mathematics, 17, Part I, 1964, p. 17.

2. Symonds, P. S. and Prager, W., "Elastic-Plastic Analysis of Structures Subjected to Loads Varying Arbitrarily Between Prescribed Limits," J. Applied Mechanics, 17, 1950, p. 315.

3. Hill, R., "The Mathematical Theory of Plasticity," Clarendon Press, 1950.

4. Poritsky, H., "Analysis of Thermal Stresses in Sealed Cylinders and the Effect of Viscous Flow During Anneal," Physics, 5, 1934, p. 405.

5. Hilton, H. H., "Thermal Stresses in Thick Walled Cylinders Exhibiting Temperature-Dependent Viscoelastic Properties of the Kelvin Type," Proc. of 2nd U.S. National Congress of Applied Mechanics, 1954, p. 547.

6. Shaffer, B. W., "Stress-Strain Relations of Reinforced Plastics Parallel and Normal to Their Internal Filaments," AIAA Journal, 2, 1964, p. 348.

7. McDanels, D. L., Jech, R. W., and Weeton, J. W., "Stress-Strain Behavior of Tungsten-Fiber-Reinforced Copper Composite," NASA Tech. Note, TND-1881, Oct. 1963.

8. Koppenaal, T. J. and Parikh, N. M., "Microstraining in Fiber-Reinforced Silver," Trans. Metal. Soc. AIME, 224, 1962.

9. Shaw, C. W., Shepard, L. A., and Wulff, J., "Plastic Deformation of Thin Brazed Joints in Shear," Trans. ASM, 57, 1964, p. 94.

10. Drucker, D. C., "Engineering and Continuum Aspects of High Strength Materials," Symposium on High Strength Materials, Univ. of California, June 1964, Brown University, Contract AT-2394, Tech. Report No. 7, June 1964.

11. Hill, R., "Theory of Mechanical Properties of Fibre-Strengthened Materials: II. Inelastic Behavior," J. Mech. Phys. Solids, 12, 1964, pp. 213-218.

4. Tensile Failure

4.1. Significance

Composites made with continuous parallel filaments which are loaded in tension parallel to the filaments presumably employ the reinforcement in the optimum manner to obtain a maximum tensile strength. The observed strengths, however, usually are a fraction of the potential tensile strength based on the strength associated with the individual fibers. The difference between the potential and observed strengths of composites must be associated with the modes of tensile failure, that is, the sequence of local fractures of individual elements of reinforcement or matrix and subsequent crack extension which eventually leads to final failure. Thus a study of tensile failure has two objectives: specification of the parameters that influence the tensile strength of composites, and suggested modifications of composites to approach their potential strength.

While parallel filament composites normally are not designed to carry large tensile stresses normal to the filaments, biaxial stresses generate such a situation. Also composites reinforced with randomly oriented fibers may experience tensile stresses normal to some filaments. Thus the parameters that control tensile strength normal to the filaments are of primary importance to the structural integrity of the composite.

4.2. Status

Composites loaded in tension parallel to the filaments will be considered in Section 4.2.1. Composites loaded normal to the filaments will be treated in Section 4.2.2.

4.2.1. Tensile Stress Parallel to Filaments

The study of tensile failure of even a simple composite containing uniaxially oriented fibers subjected to a tensile load in the fiber direction is subject to much difference of opinion. Hypotheses of strength of such composites include:

a) The assumption of uniform strain in fiber and matrix with failure stress based upon the strain to failure and the uniaxial stress-strain curves of the constituents (1).

b) Failure due to maximum bond shear stress or fiber stress (2).

c) Failure due to fiber fractures resulting from statistically distributed fiber flaws followed by interface failure (3).

d) Failure due to accumulation of fiber fractures resulting from statistically distributed fiber flaws (4).

e) Fiber fracture due to stress concentrations at fiber matrix interface (5).

f) Crack propagation failure based on flaw distribution (6).

It appears that a study of the dual problems of crack initiation and crack propagation is required. Criteria for initial fracture in matrix, fiber, or at the interface based on existing three-dimensional stress fields are required. These should include the effects of adjacent phase materials, as well as both brittle and ductile phases.

Beyond these general suggestions, the definition of the relative importance of various potential failure mechanisms quickly reflects the particular experience, views, and opinions of the authors of this report. Nevertheless, it is perhaps constructive to consider a set of related failure mechanisms and the interaction between them. This interaction serves to illustrate the fact that the relative importance of different material properties is determined by the governing failure mechanism. This is the motivation for the micromechanical studies directed toward the definition of the appropriate failure criterion.

4.2.1.1. Crack Initiation

Initial fracture may occur either in the fibers, the matrix, or interface layer. However, emphasis in the above listed hypotheses as well as from available observations of tensile failure (4,7,8) has been concentrated on initial fiber failure. Thus it is not unreasonable that in the hypotheses to be discussed, the emphasis also is on initial fiber failure.

For single fibers the statistical strength distribution criterion for fracture recommended in Section 1 provides a description of broad generality and utility. For example, the Weibull statistical strength distribution provides a reasonable fit to data exhibiting a large dispersion in strength as well as a significant length-strength size effect. With equal goodness of fit, the Weibull distribution describes low dispersion strength data and in the limit of zero dispersion it is identical to the classical concept of a maximum tensile stress theory of fracture for axial loading. It will be used in subsequent discussions of the hypotheses of tensile fracture.

4.2.1.2. Composite Failure

The initial fiber fracture can be followed by one of several possible events. The relative importance of these different failure mechanisms is likely to vary substantially with constituent properties, so that the failure mechanism for fibrous composites under uniaxial tensile stress is not unique. Three potential paths from the initial local fracture to composite failure are outlined in the following discussion.

For high strength brittle fibers, strength is dependent upon the degree of surface imperfection. When a composite of such fibers is subjected to a tensile load, a fiber fracture will occur at one of the more serious flaws or imperfections. When a fiber breaks, the stress in the vicinity of the broken fiber is perturbed substantially so that the axial stress in the fiber vanishes at the fiber break and gradually builds back up to its undisturbed stress value due to shear stresses being transferred across the fiber matrix interface. When such a break occurs, several possibilities for the future behavior of the composite exist. First, the high interface shear stresses, and/or low bond strength, could produce failure in the interface region which could propagate along the length of the fiber reducing the fiber effectiveness over a substantial fiber length. In order to achieve the potential of the fiber strength it is necessary to determine the constituent materials and fabrication conditions or coupling agents which will yield an interface sufficiently strong to prevent this interface shear failure. This can be done either through the use of a high strength bond or a ductile matrix which permits redistribution of the shear stresses. In the latter case the length of fiber which is affected by the break will increase as it will take a longer distance to retransmit the stresses back into the fiber at the low stress level of a ductile matrix. With a sufficiently strong, tough bond the interface failure can be delayed as a primary source of composite failure. A second possibility is that the initial crack will propagate across the composite resulting in failure. This is influenced by the average fracture toughness of the composite. Since with brittle fibers one can usually expect a fracture to occur at a relatively low stress level, it is important that the fracture toughness of the composite material be sufficient to prevent the propagation of this crack.

In addition to the two potential modes of failure discussed above, the fiber strength dispersion makes it likely that as the applied tensile load increases, breaks will occur randomly at other points of imperfection along the fibers. Increasing the load will produce a statistical accumulation of fiber fractures until a sufficient number of ineffective fiber lengths in the vicinity of one cross-section interact to provide a weak cross-section. At the point of incipient fracture, all of the failure modes described may very well interact to produce the final fracture.

On the microscopic level, several approximate analyses of the stress elevation in neighboring fibers caused by fracture of a single fiber have been made (4,11,15,16). In these models the parallel plane array of fibers as well as the connecting matrix are assumed to be homogeneous materials but with different elastic constants. A shear lag analysis has been employed in which the matrix is assumed to be elastic ($G \neq 0$, $E = 0$) and the fibers are either elastic (4,11) or rigid (15,16). One approximate solution has been extended to elastic-plastic matrix behavior (4). These solutions provide approximate values of the peak stress concentration in neighboring unbroken fibers, the stress elevation along neighboring unbroken fibers, and the resulting shear stress distribution in the matrix materials. These results permit an estimate to be made of the fiber length adjacent to the fiber fracture which is essentially ineffective in resisting extensional stress. If crack extension occurs, two modes are possible, one normal to the fibers and the other parallel to the fibers. The possibility of crack extension parallel to the fibers must be considered using the fracture toughness of either the matrix or interface layer, whichever is least. If crack extension does not occur, the failure mechanism would be in accordance with a statistical model.

It is assumed in the statistical model that the fibers exhibit a moderate to large strength dispersion. The "ineffective fiber length" on either side of a fiber fracture is controlled by the matrix which transfers load to the fractured fiber by shear stress until at some distance along the fiber, the tensile stress in the broken fiber approaches the average fiber tensile stress. Over this "ineffective length" the fiber load is redistributed among the remaining fibers. The composite now is viewed as a number of short lengths of composite, each with a length equal to the "ineffective fiber length." Conceptually the composite consists of a number of independent "composite links" connected in series. Fracture of the entire composite is associated with fracture of that "composite link" in which the remaining unfractured fibers are unable to sustain the load. For the conditions stated, the composite tensile strength can be estimated as the strength of a bundle of fibers (unimpregnated) with a length equal to the ineffective fiber length (4).

One important feature of the statistical analysis is that it indicates the role and contribution of the matrix material to composite strength. Without matrix the strength of a bundle of filaments may be estimated by allowing the "ineffective fiber length" to approach the composite length in the bundle statistical analysis. Introduction of matrix material provides for load transfer to broken filaments by shear, and establishes a short "ineffective fiber length." The composite strength increases as the ineffective fiber length becomes shorter.

The statistical analysis assumes that the failure load does not depend upon crack extension in the matrix or interface layer parallel to the fibers, or stress elevation and crack extension into fibers surrounding broken fibers. By contrast when the dispersion of fiber strengths is small, the stress concentration associated with a fractured fiber may dominate fracture of the entire composite. For a continuous filament composite subjected to a monotonically increasing load, the fiber stress required to fracture the first fiber is nearly equal to the stress required to fracture all of the remaining fibers. As the strength dispersion decreases toward zero, the stress concentration required to cause this "weakest link" criteron to dominate composite fracture also decreases.

Hedgepeth (9) has analyzed the stress concentration associated with one as well as more than one broken or cut filament assuming that the composite may be considered to be a homogeneous elastic orthotropic material containing a slit. Experimentally measured fracture loads for parallel "Dacron" polyester filament composites with a polyurethane elastomer matrix containing one or more cut filaments are in close agreement with the analytical estimates (10).

As implied earlier, as the dispersion of fiber strengths is decreased and/or as the stress concentration associated with a fractured fiber is increased due to an increase of the matrix shear modulus and/or yield strength, the mode of tensile fracture is anticipated to change from that described by the statistical hypothesis to that described by the weakest link hypothesis. For appropriate values of fiber and matrix parameters, experimental studies verify the primary features of each hypothesis as well as the mode of fracture (4,7,10). It remains to unify the treatment in one analysis in order to predict and experimentally verify the "fracture mode transition" from the "statistical" to the "weakest link" mode of tensile fracture.

For crack extension parallel to the fibers, the fracture toughness, $\mathcal{G}_{IIc}$, criterion can be applied to the matrix material (12,13,14). The significance of crack extension parallel to the fibers is that a stress elevation occurs in the unbroken fibers associated with the crack front as it travels along the filaments. This stress elevation essentially seeks out the weak points of the neighboring filaments, and increases the probability of fracture at such points. As additional fibers fracture, the average composite stress required for crack extension parallel to the fibers is further decreased. Once initiated, crack extension parallel to the filaments provides a mechanism leading to successive fiber fractures. This process rapidly alternates between fiber fracture and further crack extension parallel to the unbroken fibers and constitutes fracture instability that leads rapidly to final failure of the composite.

This discussion may be summarized briefly as follows: An increase in the average filament strength leads to an increase in composite strength for all three modes of tensile fracture. A decrease in fiber strength dispersion and/or an increase in fracture toughness $\mathcal{G}_{IIc}$ may cause no change in strength or an increase in strength depending upon the mode of tensile fracture. Finally an increase in the matrix shear modulus and yield strength may result in an increase, no change, or a slight decrease in composite strength depending upon the mode of tensile fracture.

Clearly, general predictions concerning the influence of a particular variable on composite strength are difficult to make independent of the mode of tensile fracture. Further, in the absence of a suitable micromechanics analysis empirically designed experimental studies frequently reveal no measurable change in composite strength clearly attributable to the test variables over the range of the variables studied (27). Conversely from observations of the appropriate modes of failure and based on appropriate micromechanics analyses, it should be possible to predict the variables that will lead to the most significant improvements in the strength of composite materials.

The discussion of the failure hypotheses was purposely limited to a small number of significant variables for simplicity. However, geometric features including fiber content and spacing, the thickness of matrix layers between fibers and consequently the relative proportion of the matrix material influenced by contact with the fibers (interface) require detailed consideration. Residual stresses including longitudinal, radial, and transverse components resulting from differential thermal contraction upon cooling and other fabrication processes must be introduced, particularly where the matrix properties and behavior are concerned (17,18,19). Similarly, the degree of constraint (state of stress) in the matrix introduced by stiffer fibers may exert a large influence on the inelastic deformation characteristics of the matrix. Finally, in real composites "flaws" are introduced unintentionally during fabrication.* Significant microscopic "flaws" may include air (gas) bubbles (20,21) matrix rich and matrix poor areas (from fabrication errors) and extraneous foreign matter.

These latter variables are all in the category of "in situ" characteristics and will require ingenious methods to separate the variables for definitive investigation.

4.2.2. Tensile Stress Normal to Filaments

In structures such as pressure vessels, biaxial stresses lead to the use of alternate layers of parallel filaments that are intentionally oriented in relation to the directions of the two principal tensile stresses. Consequently, each layer experiences tensile strains of approximately equal magnitude both parallel to and normal to the fibers.

The cross section of a fibrous composite material normal to the fibers resembles an array of circular inclusions embedded in a matrix. For small composite strains, it has been shown that low modulus matrix material experiences strains from 3 to 20 times larger than the average composite strain, depending upon the ratio of fiber modulus to matrix modulus and the volume per cent of fibers (22,23). In addition, the stiff fibers may provide high constraint with regard to inelastic deformation of the matrix (26). This combination of strain concentration and plastic constraint appears to impose high multiaxial tensile strains upon the matrix which may cause matrix fracture and/or fiber-matrix separation at small average composite strains.

---

* Only microscopic "flaws" are identified here; however "out of control" fabrication processes can lead to a significant variety of macroscopic flaws also.

In addition, residual stresses caused by differential thermal contraction and/or volume changes during cure are superimposed upon the load stresses. Photoelastic studies of thermal contraction residual stresses indicate that several patterns of potentially severe triaxial tensile residual stresses may occur, depending upon relative fiber configuration or packing (17,18,19). An urgent need exists for an elastic-plastic matrix stress analysis including the effects of strain concentration, triaxial constraint and superimposed residual stresses.

In glass fiber-epoxy composites a surprisingly high density of air bubbles has been observed to be trapped between and around fibers (20). Superimposition of this effect upon the matrix appears to greatly aggravate the triaxial strain concentrations discussed above. These air bubble flaws are anticipated to be the origin of cracks which frequently extend parallel to the filaments at small average composite strains (21). In severe cases, such cracks have been observed to reduce a structure to a series of disconnected parallel strips each containing from hundreds to thousands of fibers (21,24).

Undoubtedly the bubble problem can be reduced or eliminated through fiber-matrix wetting research studies (20) leading to appropriate fabrication process improvements. However, a criterion for crack extension involving the factors mentioned above is still needed to predict when cracking parallel to the filaments will occur.

The significance of tensile failure caused by cracks parallel to the fibers appears to be threefold. First, the interaction of periodic cracks parallel to the fibers with the tensile failure mode and strength parallel to the filaments is unknown and requires attention. Second, if the immediate effect of cracks parallel to the fibers on tensile strength is small or negligible, long time deterioration of the composite due to environmental exposure allowed by the cracks may well be more significant (21,25). Finally, the structural integrity of a composite structure containing cracks parallel to the filaments with regard to bending, shear, and compression loads appears to be seriously impaired. While these last two items are beyond the scope of this section, they are mentioned because they result from the tensile failure.

4.3. Recommendations

The following topics are recommended for immediate attention:

4.3.1. Observation of the mode of tensile failure (sequence of crack initiation(s) and extension) for a variety of composite systems loaded in tension parallel to the filaments employing interrupted tensile tests or high speed motion pictures.

These observations form the basis for analysis of the failure of various composite systems by suggesting the phenomena that must be considered of primary importance in the failure analysis.

4.3.2. Analytical and experimental study of the fracture criteria when the tensile stress is parallel to filaments.

4.3.3. Analytical and experimental study of the three dimensional stress field and criteria for fracture when tensile stress is normal to fibers.

4.4. References

1. Jech, R. W., McDanels, D. L., and Weeton, J. W., "Fiber Reinforced Metallic Composites," Proceedings of the Sixth Sagamore Ordnance Materials Research Conference, August 1959.

2. Dow, N. F., "Study of Stresses Near a Discontinuity in a Filament-Reinforced Composite Material," General Electric Co., Space Sciences Lab., Space Mechanics Memo No. 102, January 1961.

3. Parratt, N. J., "Defects in Glass Fibers and Their Effect on the Strength of Plastic Mouldings," Rubber and Plastics Age, March 1960, pp. 263-266.

4. Rosen, B. W., "Tensile Failure of Fibrous Composites," AIAA Journal, Nov. 1964.

5. Lin, T. S. and Stowell, E. Z., "Parametric Studies of Metal Fiber Reinforced Ceramic Composite Materials," Final Report, Southwest Research Institute, Jan. 1961.

6. Kies, J. A., "Prediction of Failure Due to Mechanical Damage in the Outer Hoop Windings in Fiberglass Plastic Pressure Vessels," U. S. Naval Res. Lab. Report No. 5763, Jan. 1962.

7. Rosen, B. W., "Mechanics of Composite Strengthening," General Electric Co., Space Sciences Lab., Missile & Space Div., Tech. Info. Series R64SD80. Presented at ASM Seminar on Fiber Composite Materials, Oct. 17, 1964.

8. Bouc, C. A., "A Microscopic Study of the Mode of Fracture in Filament Wound Glass-Resin Composites," Sec. 19G, 19th Annual Reinforced Plastics Conference, SPI, 1964. Also TAM Report No. 234, Univ. of Illinois, Nov. 1962, Contract Nonr 2947 (02)(X) with U. S. Naval Res. Lab.

9. Hedgepeth, J. M., "Stress Concentrations in Filamentary Structures," NASA TN D-882, May 1961.

10. Zender, G. W. and Deaton, J. W., "Strength of Filamentary Sheets With One or More Fibers Broken," NASA TN D-1609, March 1963.

11. Melvin, J. W., "Effect of Resin Property on the Fracture of FRP Laminates Models," TAM Report 249, Univ. of Illinois, 1963, Contract Nonr 2947 (02)(X) with U. S. Naval Res. Lab. (Also M.S. Thesis, June 1962.)

12. Kies, J. A. and Bernstein, H., "Recent Advances in Glass Fiber Reinforced Plastic Rocket Motors," 17th Annual Reinforced Plastics Conference, SPI, Section 6B, 1962.

4.4. References (Continued)

13. Patrick, R. L., Ripling, E. J., and Mostovoy, S., "Fracture Mechanics Applied to Heterogeneous Systems," 19th Annual Reinforced Plastics Conference, SPI, Section 3B, 1964.

Ripling, E. J., Mostovoy, S., and Patrick, R. L., "Measuring Fracture Toughness of Adhesive Joints," Mat. Res. and Standards, ASTM, Vol. 4, No. 3, March 1964, p. 129.

14. Wu, E. M., "Application of Fracture Mechanics to Orthotropic Plates," TAM Report No. 248, Univ. of Illinois, 1963, Contract Nonr 2947 (02)(X) with U.S. Naval Res. Lab.

15. Sadowsky, M. A., "Transfer of Force by High-Strength Flakes in a Composite Material," Tech. Report WVT-RR-6105-R, Watervliet Arsenal, June 1961.

16. Sadowsky, M. A. and Weitsman, Y., "Effect of Poisson's Ratio of an Elastic Filler on Force Transfer Between Embedded Mircofibers," Tech. Report WVT-RR-6108-R, Watervliet Arsenal, Sept. 1961.

17. Haslett, W. H. and McGarry, F. J., "Shrinkage Stresses in Glass Filament-Resin Systems," 17th Annual Reinforced Plastics Conference, SPI, Section 14D, 1962.

Also Fiber-Resin Interaction-I, July 15, 1961, and Resin-Glass Bond Studies-II, Aug. 15, 1961, M.C.A.-M.I.T. Plastics Research Project Progress Reports.

18. West, D. C. and Outwater, J. O., "The Stress Distribution in the Resin of Reinforced Plastics," 16th Annual Reinforced Plastics Conference, SPI, Section 19b, 1961.

19. Daniel, I. M. and Durelli, A. J., "Photoelastic Investigation of Residual Stresses in Glass-Plastic Composites," 16th Annual Reinforced Plastics Conference, SPI, Sec. 14A, 1961.

20. Bascom, W. D., "Some Surface Chemical Aspects of Glass-Resin Composites, Part I - Wetting Behavior of Epoxy Resin on Glass Filaments," U. S. Naval Res. Lab. Report 6140, Aug. 10, 1964.

21. Corten, H. T., "Reinforced Plastics," Chapter 14 in Engineering Design for Plastics. Edited by E. Baer, Reinhold Publishing Corp., New York, N.Y., 1964.

22. Kies, J. A., "Strain Magnification Factors in the Resin," U. S. Naval Res. Lab. Memo, Jan. 1962, and NRL Report 5752, March 1962.

4.4. References (Continued)

23. Schulz, J. C., "Maximum Stresses and Strains in the Resin of a Filament-Wound Structure," 18th Annual Reinforced Plastics Conference, SPI, Section 7D, 1963.

24. Rawe, R. A., "Crase Cracking and Associated Phenomena in Glass Filament Wound Pressure Chambers," Report No. M 2099, Structural Materials Div., Aerojet General Corp., 1961.

25. Brelant, S., Petker, I., and Smith, K. W., "Combined Effects of Pre-stress and Humidity Cycling Upon Filament-Wound Internal Pressure Vessels, SPE Journal, Sept. 1964, pp. 1019-1023.

26. Gurland, J., and Plateau, J., "The Mechanism of Ductile Rupture of Metals Containing Inclusions," Trans. ASM 56, No. 3, Sept. 1963, pp. 442-454.

27. Whisenhunt, Jr., F. S., "Filament-Winding Plastics, Part 2 - Role of the Resin in Glass Fiber Reinforced Structures Under Tensile Stress," Naval Research Lab. Report No. 6161, Dec. 1, 1964.

5. Failure Under Other Loads

The unidirectionally oriented filament composite obviously is ideally suited to resist tensile loads parallel to the filaments. Questions now arise concerning the behavior of the same composite in resisting other types of load, such as compression, shear, and flexure. Are the high strength/weight ratios associated with parallel filament composites limited to tension loads?

In another sense, how will a composite's capacity to resist common load histories such as repeated loads, long time steady loads, and short time impact loads compare to its static load capacity? Further, we should take into account the fact that in most cases, structural members must be designed against failure from multiaxial stresses or a succession of stresses of different types. Added to all of these loading conditions are the influences of environmental factors and defects introduced during fabrication.

Our objective here is to discuss the internal mechanics involved in some failure modes associated with various common loading conditions and to suggest lines of further experimentation and analysis.

5.1. Compression

5.1.1. Significance

Recent demonstrations of high strength to density ratios of parallel filament composites subjected to compressive loading have stimulated study of the application of fibrous composites for compression structures.

5.1.2. Status

It is convenient to consider compression parallel to the filaments first and then compression normal to the filaments.

5.1.2.1. Compression parallel to filaments

Again as in the case of tensile failure, the experimental observations are subject to conflicting interpretations. Thus, several distinct macroscopic modes of failure have been identified:

a. Progressive failure by rapid lateral displacement of one portion of a specimen relative to the adjoining portion. Initial failure is localized to a narrow band which is at approximately 45° to the direction of the compressive stress (4,6).

b. Rapid splitting parallel to fibers which separates the specimen into several specimens which may fail as in (a) or into a number of thin layers which buckle elastically (4,6,7).

c. Sudden shattering failure over the entire specimen volume, resulting in many small pieces (7).

d. Progressive splitting and disintegration of cut fiber specimen ends in the absence of adequate lateral support.

Mode (d) appears to be primarily a function of test fixture, specimen and preparation, and alignment; however, it is mentioned because it frequently obscures other phenomena of primary interest and therefore must be avoided. Also, structures with cutouts or fiber ends exposed to compressive loading may fail in this manner. The micromechanics problems associated with compressive failure are incompletely defined at this time; however, the following problems and hypotheses of modes of failure provide examples of several approaches to this problem and warrant further attention:

a. Small wave length filament buckling when the filament is supported along its length, in a fashion analogous to the buckling of a column on an elastic foundation. This is a fundamental micromechanics problem of compression failure (excluding structural buckling). For very small lateral displacements, the deformation of the interface region may be significant; however, the effect of neighboring fibers is likely to be significant at failure. Since the three dimensional stress distribution in the surrounding fibers and matrix presents a complex problem, approximate solutions and experimental determinations are urgently needed. It appears that this model leads, in first approximation, to an estimate of the potential strength of composites loaded in compression (1).

While it may be expedient to start with an infinite number of fibers, eventually the analysis for a finite number (containing edges where columns are supported only on three sides) is necessary. Conversely the problem of an edge column (support on only three sides) might be simpler and lead more directly to a useful solution. Compressive strength studies on glass cloth laminates lend indirect support to: first, the idea that at the surface where only resin surrounds the fibers on one side, the resistance to buckling is measurably reduced and leads to initial failure, and second, the presence of an adjacent fiber-matrix region measurably increases the resistance to buckling and the failure stress (2).

Beyond this first approximate model, the phenomenon of compressive failure becomes rather complex. The influence of three-dimensional residual and load stresses cannot be ignored. In addition, flaws of various kinds must be anticipated. For example, in filament-wound glass fiber-epoxy chambers, the glass fiber ends are twisted in order to retain a compact winding strand or tape. Thus, the fibers are not parallel as assumed but are present in a helical pattern. In addition, not all fibers are exactly the same length and some small per cent of the fibers are observed to break during fabrication. These latter two conditions relax the winding tension, lead to slackness, and misalignment of the fibers. Finally, during fiber impregnation, air bubbles are observed in unusually large numbers trapped among fibers (3). These air bubbles become elongated parallel to the fibers and introduce a region of reduced lateral support. The influence on fiber buckling of air bubbles requires consideration. The concept that failure is precipitated by a filament buckling into an air bubble lends itself to a simple computation of initial fiber buckling load as a function of the length of the air bubble. For medium to high composite void ratios, a significant reduction in compressive strength as a function of void content has been demonstrated; however, the precise mechanism remains unidentified (5).

The connection between fiber buckling and the macroscopic modes of failure is less well established. In a composite loaded in compression parallel to the filaments, crack extension parallel to the filaments can be caused both by elastic deformations associated with a buckled fiber which tends to separate it from its neighbor, and by shear loads among the filaments caused by nonuniform axial deformations of neighboring filaments. It is possible that this combination of phenomena which tends to produce opening mode and forward shear mode crack extension is responsible for crack extension parallel to the filaments (4). Simultaneous occurrence of fiber instability over a large volume could be responsible for those failures which occur at high stress and are described as fast or explosive. Those failures which involve lateral displacement of one portion of the specimen with regard to another can be the result of an over-all instability. Over a given length along the specimens, a group of parallel fixed end columns exhibits the lowest buckling load for this mode of buckling. Thus, the features of this mode of failure suggest that lateral instability is the criterion for failure. The matrix is stressed in axial compression to a level that approaches the matrix yield strength. Thus only a small shear stress in the matrix between the fibers causes flow, and resistance to shear displacement of one fiber longitudinally with respect to its neighbor is small.

The models discussed above are early approximations and require extensive investigation both analytically and experimentally. They have been discussed in some detail, not because they completely cover the subject of compression failure but because they provide specific examples of the types of models and analysis that will, it is believed, lead to an understanding of the factors and variables involved in failure phenomena.

5.1.2.2. Compression normal to filaments

Layers of material in a composite plate or shell structure subjected to in-plane compressive stresses can have an important effect upon the composite failure. Failure mechanisms for compressive stress normal to the filaments have received relatively little detailed study;

however, two modes of failure have been observed:

a. Failure by cracking on a plane parallel to the filaments and at an angle of about 45° to the direction of the stress.

b. Failure by cracking on a plane parallel to the filaments and parallel to the compressive stress.

As in the case of tension normal to the fibers, the high modulus fibers act as rigid inclusions in the matrix. Between two closely spaced fibers, strain concentration could occur. The resulting stress field could result in a shear failure in the matrix, in an interface separation leading to a longitudinal failure, or in inelastic flow and collapse of the composite.

5.1.3. Recommendations

The mechanics of composite compression failure are not well understood. Analytical models which have been proposed are approximate in nature and definitive observations of failure mechanisms are lacking. Consideration of inelastic effects and interactions of several potential failure modes complicate the problem. Accordingly, the principal areas for initial effort appear to be:

5.1.3.1. Perform controlled experiments which define the failure mechanisms and the important material mechanical and geometric properties.

5.1.3.2. Apply existing techniques for elastic instability analyses to this problem, postulating a wide range of possible buckling configurations.

5.1.3.3. Attempt to relate fibrous composite failure mechanisms to the knowledge of deformation and fracture of particulate composites.

5.1.4. References

1. Rosen, B. W., "Mechanics of Composite Strengthening," ASM/Metals/Materials Congress, Oct. 1964.

2. Boller, K.H., "Effect of Thickness on Strength of Glass-Fabric-Base Plastic Laminates," U.S. Forest Products Laboratory Report No. 1831, May 1954.

3. Bascom, W.D., "Some Surface Chemical Aspects of Glass-Resin Composites, Part I - Wetting Behavior of Epoxy Resins on Glass Fibers," U.S. Naval Research Lab. Report No. 6140, 10 Aug 1964.

4. Gillman, James, and Corten, H. T., "Mechanics of Failure of Glass Reinforced Plastics Under Compressive Loads," Final Report on Contract Nonr-3985(05) in preparation.

5. Fried, N., "The Response of Orthogonal Filament Wound Materials to Compressive Stress," Proc. 20th Annual Conf. SPI, Sec. 1c, Feb. 1965.

6. Levenetz, B., "Optimum Fiber Diameter," Supplementary Report to Annual Summary Report, U.S. Navy, Bureau of Ships, Contract NObs-86347, 25 Dec. 1964.

7. Rosen, B. W., and Ketler, Jr., A. E., "Hollow Glass Fiber Reinforced Plastics," G.E. Space Sciences Laboratory, Report R 63SD41, May 1963, on U.S. Navy Bureau of Naval Weapons Contract NOw-61-0613-d.

5.2. Shear and Flexure

5.2.1. Significance

Shear and flexure are considered together because serious shear stresses may be produced by local bending. For example, in structures such as internally and externally pressured cylindrical shells, because of constraint (reinforcing rings, heads, skirts, openings and fittings), both shear and flexure occur.

Thin laminates are sometimes employed as shear panels to stiffen light-weight structures. Under these circumstances the panel may experience in-plane pure shear loading.

Fundamentally pure flexure combines uniaxial tension and compression states of stress in one member. Simple flexure adds horizontal shear stresses. One important difference between flexure and axial loading appears to be the stress or strain gradient present in flexural members which contributes to the significant size effect in glass fiber-resin composites.

Because of the ease of testing, flexure is a common form of loading for mechanical property determination. However, the associated combined state of stress complicates the interpretation of test results. Thus the beam geometry strongly influences the relative importance of the different stress components.

5.2.2. Status

Pure shear applied in the plane of a thin laminate commonly has been studied to determine shear modulus and strength of glass cloth laminates (1,2). Since this topic falls primarily in Section 6, Laminates, further mention will be deferred.

From the micromechanics point of view, it is necessary to retreat from the complex cloth reinforcement to the simpler parallel filament composite at this stage of development. For a pure shear state of stress applied in a plane normal to the filaments or in the plane of a series of filaments, large matrix strain magnifications have been demonstrated (3,4). Although these analyses are approximate, there can be no doubt concerning their qualitative validity. This strain magnification, while slightly smaller than the values associated with tensile stresses normal to the filaments, imposes a severe shear strain upon the matrix material and interfacial layer between closely spaced fibers. From the available analyses (3,4), strain magnifications of from 3 to 17 are anticipated, depending upon the volume fraction (spacing) of fibers. As in the case of a tension stress normal to the fibers, the behavior of the thin layer of matrix material and interfacial layer are unknown. It would be anticipated, however, from the normal behavior of homogeneous matrix resins that the maximum allowable strains would be larger in shear than in tension.

With glass-epoxy parallel filament composites, and presumably to some extent with other systems, this problem is complicated by the fact that air bubbles are trapped in the matrix, particularly around and adjacent to the reinforcing fibers during fabrication, due partially to inadequate wetting of the fibers by the resin (5). The presence of these air bubble flaws aggravates the strain magnification problem (13) and changes it to one of flaw or crack extension. Linear elastic fracture mechanics has been applied to measure the fracture toughness, $\mathcal{G}_{IIc}$, for pure shear loading of a parallel filament composite (6) and for a thin layer of resin between either metal or glass adherends (7). These studies indicate that the resistance to crack extension in the forward shear mode measured by the fracture toughness, $\mathcal{G}_{IIc}$, is greater, approximately by a factor of 3 to 4, than the fracture toughness of the opening mode fracture, $_{Ic}$. Current work is concerned with establishing the interaction curve for combinations of opening and forward shearing modes of crack extension (6,7,8,9). See Section 5.3, Multiaxial States of Stress.

While flexure is a common type of loading and frequently is used to measure the mechanical properties of composites, observations of the mode of failure have been reported only rarely. This may result from incomplete documentation, or it may be a consequence of the influence of the combined state of stress which yields a failure mode of uncertain origin.

The scattered comments concerning mode of failure of cloth laminates loaded in flexure, pieced together, indicate that failure frequently occurs on the compression side by outer layer separation and buckling (cracking parallel to the fibers) or crushing due to loads normal to the fibers. Presumably these are common modes of failure for long slender beams. In one study of parallel filament composites (Scotchply), a similar mode of failure was observed (12). Occasionally failure on the tension side will accompany or follow failure on the compression side of a beam.

For short deep beams, failure in shear along the neutral axis is commonly observed. This type of test has become a standard for measurement of shear strength parallel to the fibers.

In either tension or compression, the failure mode is expected to resemble that in simple tension or compression but with the added influence of the stress or strain gradient (or volume of highly stressed material). An effect observed in flexure to a degree more pronounced than in either tension or compression is a size and/or shape effect. The shape effect has been represented in terms of the length to depth ratio for rectangular cross-section beams. The influences of size and shape (ℓ/d), if they are separate have not however been definitively separated, nor studied in detail for parallel filament construction. The available data exhibit a very large decrease in strength with increase in the length of a beam, an effect that is difficult to attribute entirely to the flaw theory of size effect (12). Certainly this size and shape effect deserves immediate attention both because of its implications regarding mechanism of failure (flaw theory) and because of its practical implications regarding the strength of large structures.

5.2.3. Recommendations

5.2.3.1. For parallel filament composites, the strength in shear parallel to the filaments in a short beam has been intuitively recognized and used as a measure of the combined effects of fiber-interface region matrix bond, the strain magnification due to geometry of fiber spacing, and flaw (air bubbles) concentration. This test is excellent for comparison of the quality of two composites, however, when used to obtain quantitative data on a particular material, the test is a challenge to the mechanics analyst. For this approach, it is necessary to perform:

(a) A three-dimensional elastic and elastic-plastic analysis of strain magnification eventually including an interface layer with properties different from the matrix.

(b) Measurement of the fracture toughness, $\mathcal{G}_{IIc}$, for crack extension from a flaw for simple geometries, observing the path of crack extension, i.e., in the matrix or interface layer for various typical composite systems.

(c) Recombination of the geometric features, residual stresses, etc. and the fracture toughness measurement to deomonstrate that all of the significant features of the fracture mode were taken into account in the micromechanics analysis.

5.2.3.2. Observations of mode of failure in flexure should be made for a variety of systems. Systems representative of different relative strengths in tension, compression, and shear should be investigated to insure observation of all possible modes of failure.

5.2.3.3. Behavior in flexure should be correlated with behavior in tension, compression, and shear. Analysis of flexural behavior based on the axial tension and compression behavior, both elastic and plastic, is needed.

5.2.3.4. Size and shape effects in flexure deserve immediate attention and correlation with mode of failure and the significant flaws. The rather large size effect observed in composites in flexure may be caused partially by flaws and partially by uncontrolled manufacturing variables as the specimen size is increased. The influence of flaws typical of a particular system should be carefully separated from manufacturing variables typical of different specimen sizes.

5.2.4. References

1. Werren, Fred, "Direction Properties of Glass-Fabric-Base-Plastic Laminate Panels of Size That Do Not Buckle," Forest Products Lab. Reports 1803 (April 1950) and 1803A (March 1956).

2. Werren, Fred, "Mechanical Properties of Plastic Laminates," Forest Products Lab. Reports 1820 (1953) and 1820A (1960).

3. Kies, J. A., "Strain Magnification Factors in the Resin," NRL Report 5752, March 26, 1962.

4. Schulz, J. C., "Maximum Stresses and Strains in the Resin of a Filament-Wound Structure," 18th Annual Reinforced Plastics Conference, SPI, Section 7D, Feb. 1963.

5. Bascom, W. D., "Some Surface Chemical Aspects of Glass-Resin Composites, Part I - Wetting Behavior of Epoxy on Glass Filaments," U.S. Naval Res. Lab. Report 6140, Aug. 10, 1964.

6. Wu, E. M., "Application of Fracture Mechanics to Orthotropic Plates," TAM Report 248 to NRL, Contract Nonr 2947(02)(X), June 1963, and Wu, E. M. and Reuter, Jr., R. C., "Crack Extension in Fiberglass Reinforced Plastics," TAM Report 275, Univ. of Illinois, Feb. 1965 on U.S. BuWeps Contract No. Now-0204-d.

7. Ripling, E. J. and Mostovoy, S., "Factors Controlling the Strength of Composite Bodies (Interphase Fracturing of Composite Bodies)," Materials Res. Lab., Inc., Quarterly Progress Report No. 2 to Bureau of Naval Weapons Contract No. Now 64-0414-c Aug. 1964.

8. Mast, Philip, Mechanics Div., U.S. Naval Research Laboratory, Washington, D.C., private communication.

9. Erdogen, F., "Stress Distribution in Bonded Dissimilar Materials with Cracks," ASME Preprint 64 WA/APM-32.

10. "Proposed NOL Ring Test Method for Parallel Glass Roving Reinforced Plastics: Evaluation of Chemical Finishes," NAVORD Report 5680, July 1, 1957.

11. Elkins, R. A., Levenetz, B., and Duft, B. L., "Interlaminar Shear of Filament-Wound Reinforced Plastics," Quarterly Progress Report Narmco Res. & Development for Naval Ordnance Lab., Contract N 60921-7094.

5.2.4. References (Continued)

12. McGarry, F. J., "Flexural Behavior of Fiberglass Laminates," 16th Annual Reinforced Plastics Conference, SPI, Section 13E, 1961.

13. Paul, J. T. and Thomson, J. B., "The Importance of Voids in the Filament Wound Structure," Proc. 20th Annual Conference, SPI, Section 12c, Feb. 1965.

5.3. Multiaxial States of Stress

5.3.1. Significance

The term "multiaxial states of stress" refers to the applied stress since even the simplest uniaxial states of applied stress result in multiaxial states of internal stress.

While parallel filament composites may be most efficient for axial loads and even designed to carry primarily axial loads, all structures experience multiaxial states of stress due to fabrication misalignments, unexpected service loads, and joining methods. As a result multiaxial states of stress play an important role in many failure phenomena.

Further many composite structures consist of layers of filaments laid up or wound at different angles, that is, laminates. One of the primary tasks of a theory of failure for a parallel filament composite is to provide some of the necessary tools to treat the problem of failure of laminates.

5.3.2. Status

Two points of view on this question are possible. First, borrowing the macroscopic approach of the mechanics of homogeneous materials, one can ask what component of stress or invariant of the stress tensor provides a suitable criterion for failure? The second approach, micromechanics, takes cognizance of the two or three phase nature of the composite and treats each phase as a different homogeneous material.

5.3.2.1. Macromechanics

A beginning has been made by Norris (1) who proposed the use of the energy of distortion theory of failure in conjunction with a material model of homogeneous isotropic material containing voids in the shape of equal rectangular prisms. The voids leave a solid consisting of three sets of thin orthogonal interpenetrating walls which are aligned to coincide with the principal material directions. Each wall (except at the intersections) is subjected to biaxial stresses. The stress concentration at the intersection of the walls is neglected in the analysis of the model. By using the experimental strength values in principal material directions to evaluate constants, Norris demonstrated reasonable agreement with data for plywood and glass fiber cloth reinforced plastics (1) tested in tension, compression, and shear, in other directions.

A second macroscopic approach to this problem for parallel filament composites is concerned with a fracture criterion in terms of applied multiaxial stresses that will cause crack extension from an existing crack or flaw in orthotropic material. Wu (3) has studied this problem analytically and experimentally using balsa wood and Scotchply (6) and determined the combinations of K_I (opening mode) and K_{II} (shear mode) that cause crack extension. Work currently is under way on combined compressive and shear loading. In both cases the axial stress is taken normal to the crack and the crack is parallel to the fibers. The axial stress component parallel to the fibers theoretically has no influence on crack extension. Thus the problem for biaxial stresses should be completely covered by these two cases.

Mast (4) has suggested that for crack extension the combined rates of release of elastic strain energy, $\mathcal{G}$, should be equal to the fracture toughness, $\mathcal{G}_c$. That is $\mathcal{G}_I + \mathcal{G}_{II} = \mathcal{G}_c$. This proposal is under investigation to determine the causes of deviations of the experimental data from this concept (6).

5.3.2.2. Micromechanics

To relate failure to the behavior of the constituent materials, the fibers, the matrix, and the interface layer, the micromechanics view is essential. A treatment of the strain concentration in the resin when axial and shear stresses are applied in a plane normal to the filaments is one treatment of multiaxial stresses in plane strain (5). Since this approach was mentioned previously for axial loading and is essentially identical to multiaxial loading in a plane normal to the fibers, it will not be repeated except to note that the stress analysis is approximate and requires additional experimental verification.

In an attempt to localize the area where multiaxial states of stress will have the greatest influence, it is useful to note that there appears to be no reason to anticipate that multiaxial stresses with one component of tension parallel to the filaments will cause different filament fracture behavior than the same uniaxial tension parallel to the filaments.

However, an influence of multiaxial stresses upon crack extension parallel to the filaments is anticipated. Several cases are of interest. If fiber fracture precedes cracking parallel to the filaments, multiaxial tensile stresses may contribute to crack extension in the matrix. Therefore for a given matrix material, the same initial random fiber fracture behavior would be expected; however, the ultimate strength of the composite may or may not be lower because of interaction with crack extension parallel to the filaments. Conversely, if fiber fracture is not present because the tensile stress parallel to filaments is small, no effect of this tensile stress would be anticipated until it caused initial fiber fracture. If the tensile stress normal to the filaments had previously produced many cracks parallel to the filaments, each strand of filaments would act independently as a tensile member. If each strand contained many fibers, the tensile strength parallel to the fibers might still be unaffected. However, cracking parallel to the filaments may "open" the composite to adverse environmental effects.

As observed in Section 5.1, compression failure by local fiber buckling appears to occur easier at a surface where the outside fibers experience less constraint. Thus, cracking parallel to the fibers produces a composite that is ill suited to resist subsequent compressive loads parallel to the fibers, both from the point of view of buckling of surface fibers and structural buckling of the now unsupported strands of fibers. Since shear stresses in the plane of a parallel filament composite are resisted entirely by the matrix, extensive cracking parallel to the filaments destroys the shear resistance.

These considerations may be summarized by noting that while multiaxial states of stress do not have a direct adverse effect upon the behavior and strength of the filaments, if the multiaxial state of stress causes or contributes to matrix cracking parallel to the filaments, the integrity of the structure is partially impaired or completely destroyed, and the composite reverts toward a number of composited strands of fibers. For all states of stress except tension parallel to the fibers, the structure has failed. For tension parallel to the fibers, the strength may be indirectly impaired as a result of adverse environmental influences.

5.3.3. Recommendations

5.3.3.1. It is recommended that the utility of macroscopic theories of failure for anisotropic materials be explored. The collection of a suitable body of experimental data concerning failure under various multiaxial states of stress is required. The experiments should be designed to evaluate the "load path dependency" of failure for critical cases.

5.3.3.2. Experiments should be designed to delineate combinations of multiaxial states of stress that cause detrimental interactions between cracks initiated by fiber fractures or buckled fibers and crack extension parallel to the fibers. Various combinations of multiaxial stress should be explored to locate areas where the components of multiaxial stress produce unusually large effects.

5.3.4. References

1. Norris, C. B., "Strength of Orthotropic Materials Subjected to Combined Stresses," Forest Products La.. Bulletin No. 1816, March 1955.

2. Leon, G. S., "Analysis of the Failure of Solid Fuels Under Combined Stresses," Status Report DSR 8742, M.I.T.

3. Wu, E. M., "Application of Fracture Mechanics to Orthotropic Plates," TAM Report No. 248, June 1963, to U.S. Naval Research Laboratory, Contract Nonr 2947 (02)(X).

4. Mast, Philip, Mechanics Div., U.S. Naval Research Laboratory, Washington, D. C. Private communications.

5. Kies, J. A., "Maximum Strains in the Resin of Fiberglass Composites," U.S. Naval Research Lab. Report No. 5752, 26 Mar. 1962.

6. Wu, E. M. and Reuter, Jr., R. C., "Crack Extension in Fiberglass Reinforced Plastics," TAM Report No. 275, Univ. of Illinois, Feb. 1965 on U.S. BuWeps Contract No. No-w 65-02 04-d.

5.4. Creep and "Stress Corrosion"

5.4.1. Significance

Practical utilization makes it necessary to extend the range of applicability of any material to encompass wide variations of ambient conditions such as temperature and humidity, both of which affect, in particular, the performance of fiber-reinforced plastics. While the high temperature behavior of glass reinforced plastics is an area of current concern, the fiber-reinforced metals will undoubtedly require more work in this area in the future to develop their great potential usefulness at much higher temperatures.

5.4.2. Status

The creep behavior of reinforced resins, particularly glass fabric reinforced, has been measured under carefully controlled environmental conditions (1,2,3,4,5). The current state of the theory, because of the complexity of these fabric systems, is concerned largely with the empirical fitting of the mathematical equations to the experimental curves (1,3).

In parallel filament glass-resin composites loaded in tension along the filaments, there is a question concerning the mechanism of creep deformation. It is known that the glass filaments do not creep a measurable amount at room temperature. Therefore, after a period of initial readjustment of stress, creep may cease until some filaments fracture by static fatigue. The mechanism of creep in tension along the filaments is in need of exploration and clarification, at both room and elevated temperature.

In compression and shear, the resin may be expected to creep with only moderate restraint from the fibers. Only preliminary studies have been completed in this area (6,7) and much additional work, both experimental and analytical, is required. Often the viscoelastic behavior can be described if the corresponding elastic solutions are known, but mechanistic explanations on the micromechanics level are needed.

Severe degradation is encountered in resin-base composites which are exposed to the combined action of moisture, stress, and temperature, and in many cases this limits the applicability of the material. While failure is believed to be due to failure at the interface between glass and resin (8), it is not only an interface problem, since presumably the moisture penetration is facilitated by microcracks associated with internal strain concentrations (9). In addition, glass fibers themselves are subject to static fatigue, presumably a form of "stress corrosion," influenced by the moisture content of the environment. This is an active problem area, which requires an evaluation of the interaction of mechanical and chemical effects (10,11,12).

Recently the tensile behavior of composites consisting of parallel ceramic or metal fiber reinforced metal matrices have been explored at elevated temperature including creep and rupture in several instances (13, 14, 15). These studies have demonstrated significant reinforcement with small volume percentages of fiber (13, 15), significant tensile strength very close to the melting temperature of the matrix materials (13), and a significant reduction in creep strains and increase in rupture life, as compared to unreinforced matrix material (15).

Some of the problems encountered with these composites are associated with the interaction between the fibers and matrix. With metal fibers and metal matrix the contact between the two dissimilar metals at the interface may create a very steep composition gradient. Diffusion of one metal into the other is governed by the temperature and the nature of the equilibrium alloy phases. While diffusion is believed to be necessary to the formation of a bond between fiber and matrix, it may influence the mechanical properties by changing the width and composition of the transition region, forming solid solutions or intermetallic compounds or even causing recrystallization in the fiber material (17, 18).

With ceramic whiskers, such as Al_2O_3, liquid metal matrices do not readily wet or bond to the whiskers. Metal coatings applied to the whiskers prior to infiltration, for the purpose of enhancing the wetting and bonding, involve interaction problems similar to those with metal fibers.

From a micromechanics point of view, these in situ changes in the constituent materials are a function of time and temperature and may involve degradation of the fiber or matrix properties. Thus, creep and rupture behavior at elevated temperatures will also reflect the changing constituent properties.

5.4.3. Recommendations

5.4.3.1. For parallel composites loaded in tension parallal to the filaments experimental investigation is needad to determine the conditions for creap and stress rupture, i.e., the stress, strain, time, temperature relations, and tha micromechanics mechanisms of creap and ruptura.

5.4.3.2. Closely associated with creep and rupture phenomena is the need to extend experimentation designed to separate the individual mechanisms of matrix, interface, and fiber degradation. The solution of this problem is, by necessity, intimately associated with an understanding of the bond between fibers, interface region, and matrix, and the changes which occur with time and temperature.

5.4.4. References

1. Boller, K. H., 14th Annual Conference, SPI, FRP Division, Feb. 1959.

2. Findley, W. N., Peithman, H. W., and Worley, W. J., "Temperature Property Relations in Melamine and Silicone-Glass Fabric Laminates," Modern Plastics, March 1957.

3. Findley, W. N., "Prediction of Performance of Plastics Under Long-Time Static Loads," Trans. The Plastics Inst. Proc. Conf. on Testing for Performance, Vol. 30, No. 87, June 1962.

4. Goldfein, S., "Creep of Glass-Reinforced Plastics," ASTM Bulletin, Oct. 1957, pp 29-36, and Discussion by Simmons, W. F., pp 65-66.

5. Goldfein, S., "Long Term Rupture and Impact Stresses in Reinforced Plastics," ASTM Bulletin, Sept. 1957, pp 36-39.

6. Cornish, R. H., Nelson, H. R., Broutman, L. B., and Abbott, B. W., "An Investigation of Materials Parameters Influencing Creep and Fatigue Life in Filament Wound Structures," Sixth Quarterly Report, I.I.T. Res. Inst., Dec. 1963, for U.S. Navy Bureau of Ships, Contract No. NObs 86461.

7. Abbott, B. W., "Some Observations on the Biaxial Compressive Creep Performance of Filament Wound Laminates," I.I.T. Res. Institute Special Tech. Report, Aug. 1964, for U.S. Navy Bureau of Ships, Contract NObs 90329.

8. Rawe, R. A., Trans. Plastics Institute, Vol. 30, No. 39, 1962.

9. Outwater, J. O. and Seibert, W. J., "The Effect of Water on the Strength of Laminated Pressure Vessels," NRL Tech. Memo No. 194, Contract Nonr 3219(01)X, Oct. 1962.

5.4.4. References (Continued)

10. Cameron, N. M., "An Investigation of the Effect of Environmental Treatments on the Strength of E-Glass Fibers," TAM Report No. 274, Jan. 1965. Univ. of Illinois for U.S. Bureau of Naval Weapons, Contract NOw 64-0178-d.

11. Hollinger, D. L. and Plant, H. T., "The Role of Stress Corrosion in Glass Fibers," Proc. 19th Annual Conference SPI, Section 11A, Feb. 1964.

12. Schmitz, G. K. and Metcalfe, A. G., "Characteristics of Flaws on Glass Fibers," Proc. 20th Annual Conference SPI, Section 3A, Feb. 1965.

13. Sutton, W. H., Chorne, J., Gatti, A., and Feingold, E., "Development of Composite Structural Materials for High Temperature Applications," Thirteenth Progress Report, June 1, 1963 - Aug. 31, 1963, Space Sciences Lab., General Electric Co. for Bureau of Naval Weapons, Contract NOw 60-0465-d, Aug. 1963.

14. Dean, A. V., "The Development of Composite Materials for Service at Medium and Elevated Temperatures," Applied Materials Research, Vol. 3, No. 4, Oct. 1964, p. 195.

15. Ellison, E. G. and Harris, B., "The Elevated Temperature Properties of a Nickel Alloy Reinforced with Tungsten Wires," Applied Materials Research, 1965.

16. Sutton, W. H., Chorne, J., and Gatti, A., "Development of Composite Structural Materials for High Temperature Applications," Sixteenth Progress Report, 1 March 1964 - 30 May, 1964, Space Sciences Lab., General Electric Co. for Bureau of Naval Weapons, Contract NOw 60-0465-d, June 1964.

17. Baskey, R. H. et al, "Fiber-Reinforced Metallic Composite Materials Interim Progress Report, 1 Nov. 1964-31 Jan. 1965, Mechanical Res. Div. Clevite Corp. for Air Force Materials Lab., Contract AF 33(615)2172.

18. Petrasek, D. W. and Weeton, J. W., "Alloying Effects on Tungsten-Fiber-Reinforced Copper-Alloy or High-Temperature-Alloy Matrix Composites," NASA TND-1568, Oct. 1963.

5.5. Fatigue

5.5.1. Significance

Experience with homogeneous materials as well as composites leaves no doubt that repeated loads cause progressive failure at stress levels lower than the one cycle ultimate strength. Thus, the detrimental effects of repeated loads, the second and/or the millionth cycle, become an essential part in the description of behavior and failure criteria for all structural members.

5.5.2. Status

The fatigue behavior of a variety of glass cloth reinforced plastic laminates has been investigated by Boller (1,2,3) and others (4, 5,6). Typical cycle dependent fatigue behavior is observed. The influence of stress concentration, moisture, temperature, direction of loading, level of mean stress and type of fabric reinforcement have been studied. It is believed that many failures initiated in the interface layer between fibers and matrix.

In parallel glass filament-plastic composites, Cornish, et al (7) found that the fatigue strength was a larger percentage of the static compressive strength than was found for cloth reinforced laminates. Also they made a number of detailed observations of the failure mechanism in compression, for static (one cycle), creep, and fatigue loading. Observing the cross-section normal to the fibers with either the light or electron microscopes, they found cracks very close to and parallel to the filaments for all three types of loading, at a load of 80 per cent of the static compressive strength of the material. They observed that the mode of failure, cracking in the glass-resin interface region, was essentially similar for all three types of loading; however, both creep and fatigue conditions accentuated the degree of cracking. At the time that these specimens were removed from test for examination, they still sustained the applied load. Thus, these observations were all made during a crack extension portion of the life after the initiation of local failure but before final failure was evident by macroscopic observation or loss of load sustaining capacity.

Of the constituent materials, the crystalline and polymeric forms are all believed to be susceptible to crack initiation and propagation caused by cyclic loading. Conversely, the glassy phase materials have been demonstrated to be susceptible only to static fatigue where time under load and environment are significant. Thus, in planning studies of fatigue failure of composites, cognizance should be taken of the failure mechanisms of the constituent materials as an aid in choosing the significant variables.

In both cyclic fatigue and static fatigue of homogeneous material, initial cracking is intimately associated with stress or strain concentrations. Thus, in laminates, the flaws, including geometric discontinuities, air bubble and foreign particle inclusions, and regions of environmental attack are anticipated to be critical locations for crack initiation. Also the scatter characteristic of fatigue life and strength measurements is believed to be largely attributable to the severity of the initial flaws. Thus, control of fabrication variables again takes on a role of major importance if significant micromechanics results are to be obtained.

5.5.3. Recommendations

5.5.3.1. Observation of the mode of failure, that is, the sites of crack initiation as well as the path of crack extension are important. If it can be demonstrated that the modes of failure in fatigue, creep, and static loading are similar with regard to location of crack initiation and crack extension, then time and effort can be reduced by treating these three types of loading together, at least from the micromechanics point of view. Further it is anticipated that improvement in the static strength of composites will reflect similar improvements in the fatigue and stress rupture strengths. This requires confirmation with regard to the quantitative values.

5.5.3.2. Behavior, including failure, of constituent materials under repeated loading should be related to the behavior of the composite. Because of the insensitivity of glassy phase materials to repeated loading, attention should be given to the cyclic test frequency for correlation with time and temperature at stress in steady load tests.

5.5.4. References

1. Boller, K. H., "Fatigue Tests of Glass-Fabric-Base Laminates Subjected to Axial Loading," Forest Products Laboratory Report 1823, May 1952.

2. Boller, K. H., "Fatigue Properties of Various Glass-Fiber Reinforced Laminates," WADC Tech. Report 55-389, May 1956.

3. Boller, K. H., "Fatigue Properties of Plastic Laminates Reinforced with Unwoven Glass Fibers," Forest Prod. Lab., ASD-TDR 62-464, Sept. 1962.

4. Lazan, B. J. and Anderson, V. W., "Damping and Fatigue Properties of Plastic Materials," University of Minnesota, 1958.

5. Davis, J. W., McCarthy, J. A., and Schurb, J. N., "The Fatigue Resistance of Reinforced Plastics," Materials in Design Engineering, Dec. 1964, pp 87-91.

6. Thompson, Trans. Plastics Inst., Vol. 30, No. 50, 1962.

7. Cornish, R. H., Nelson, H. R., Broutman, L. J., and Abbott, B. W., "An Investigation of Material Parameters Influencing Creep and Fatigue Life in Filament Wound Laminates," Sixth Quarterly Report, Dec. 1963. Contract No. NObs 86461, BuShips.

8. Forsyth, P. J. E., George, R. W., and Ryder, D. A., "Some Preliminary Tests on Aluminum Alloy Sheets Reinforced with Strong Wires," Applied Materials Research, Vol. 3, No. 4, Oct. 1964.

9. Baker, A. A. and Crotchley, D., "Metallographic Observations on The Behavior of Silica Reinforced Aluminum Under Fatigue Loading," Applied Materials Research, Vol. 3, No. 4, Oct. 1964, pp 215-222.

5.6. High Speed Loads

5.6.1. Significance

The actual and potential uses of fiber-reinforced materials in such applications as body armor and satellite shielding require an understanding of the behavior under impact loads.

5.6.2. Status

Numerous tests of fibers have been made in direct tension or by transverse loading at high velocity. Similar tests have been made on woven fabrics. There is a large body of results of empirical tests of fabric-resin laminates for personnel armor impacted by high-velocity slugs. The theory of behavior of fibers under such transient stresses is less advanced than the static theory, and the combinations of fibers and fabrics with matrices under such stresses are still less well understood.

Little effort appears to have been directed toward the analysis of the micromechanisms of failure. One paper (1) observed that the tensile and interlaminar shear strengths increase with loading rate, and it also reported a change of the stress-strain curve. The higher the rate of loading, the fewer individual local flaws were observed before final failure. The analysis by Hedgepeth (2) of dynamic overshoot when filaments are suddenly broken, appears to point the way toward a quantitative understanding of the phenomena..

As a contribution to the design of composites, Kelly (3) proposed that ductility would be increased if discontinuous fibers were used in a ductile matrix, so that the matrix could take part in the elongation. The strength, then, could be maximized by optimizing the length of the fibers.

A great deal of analytical and experimental research will be needed to elucidate micromechanical behavior and to take full advantage of the potentialities of these composites.

5.6.3. Recommendation

Experimental and theoretical analysis of failure mechanism of fiber bundles under high speed loads. Application of modified statistical models and crack propagation theories to dynamic situations.

5.6.4. References

1. McAbee and Chmura, 16th Conference FRP Group SPI, 1961.

2. Hedgepeth, J. M., "Stress Concentrations in Filamentary Structures," NASA Tech. Note D-882, 1961.

3. Kelly, A., "The Strengthening of Metals by Dispersed Particles," Proc. Royal Soc. A, 282, 1964, p. 63.

5.7. Other Environments

5.7.1. Significance

The opportunity to form a material by the combination of two or more principal constituents offers the potential of achieving a composite which can respond favorably to more than one major element of the environment. Thermo-structural composites are the most prominent type of materials whose study falls within this area. The use of composite materials for re-entry vehicle heat shields which provide thermal and structural protection for the payload, or for combined micrometerorite and thermal radiation shields to protect cryogenic space vehicle fuel tanks are examples of potential applications which require an analytical definition of the nature of desirable constituent properties. Further examples of materials for "composite environments" are: electrical-mechanical composites--such as, radome structures, or structures which can attenuate incident electromagnetic energy, acoustic-structural composites--such as, structures which can attenuate incident acoustic energy.

5.7.2. Status

5.7.2.1. Thermal Effects

The use of a composite material, even at a uniform elevated temperature, introduces thermal stress problems. The uniform temperature problem for simple geometries can be treated by methods similar to those discussed in Section 2.1, Typical Elements (Elastic). The thermal stresses for realistic composites involve the problems of geometry definition discussed in Section 2.2, Average Stress-Strain Behavior (Elastic). In fact, the definition of coefficient of thermal expansion (1) very closely follows the analyses for elastic constants. The thermal conductivity has also been studied (1) and since the specific heat is available from a "rule of mixtures" expression, thermal stress problems can be evaluated using the techniques available for thermal stress problems in anisotropic media. The emphasis on the approach for composite materials should perhaps be on performing multiple functions with a single material.

5.7.2.2. Acoustic Effects

Since the transverse fiber dimensions are small compared to the wave lengths of acoustic disturbances, it seems reasonable to expect that a fibrous composite will respond acoustically as an effectively homogeneous but anisotropic material. Thus, the acoustic impedances in the various directions can be readily obtained from the elastic constants of the material. It appears that loss tangents are not likely to lend themselves to theoretical evaluation and that experimental studies should be utilized.

5.7.3. Recommendation

Perform parametric studies of potential of a single composite to perform multiple functions (e.g., thermo-mechanical protection systems) to assess the need for future micromechanics work in this area.

5.7.4. Reference

1. "Hollow Glass Fiber Reinforced Laminates," Final Report for Bureau of Naval Weapons under Contract NOw-63-0674-c, General Electric Company, Space Sciences Laboratory, Valley Forge, Pa., September 1964.

6. Laminates

6.1. Significance

Although laminates made of or incorporating fibrous composite materials may in some ways be considered to be structures rather than materials, and therefore outside the purview of this Committee, there are aspects of the internal mechanical behavior of these composites that are in need of investigation and should be considered here because this behavior is an extension of the micromechanics of fibers and matrices as examined above.

6.2. Status

6.2.1. Classes of Layered Fibrous Composites

Fiber-based laminates take many forms, but the layers of fibrous materials composing such laminates fall into the following principal classifications:

Randomly-oriented chopped fiber.

Randomly-oriented continuous fiber in a swirl pattern.

Woven fabrics:

> Continuous filament yarns or staple yarns.
>
> Balanced, i.e., equal number of yarns in machine and cross direction.
>
> Unbalanced, i.e., more yarns in one direction than in the other.
>
> Various weaves, e.g., plain, basket, satin, etc.

Parallel filament or yarns, unwoven.

Braid and other nonorthogonal patterns.

In randomly-oriented chopped fiber combined with a matrix, the problems of micromechanics are essentially as outlined in preceding sections of this report. The problems of unwoven parallel filament yarns are also similar to the problems of micromechanics discussed above. Randomly-oriented continuous fiber in a swirl pattern introduces the factor of curvature in the fibers embedded in a matrix.

Woven fabrics and braids involve the complex behavior of crimped and interwoven fibers or yarns when subjected to stress. The behavior of weaves and braids as such is not directly of concern to this Committee, but falls in the province of textile behavior. When such fabrics are combined with a matrix to form a composite, the internal mechanical interactions between the fabric and the matrix come into the category of the micromechanics of composites. Even when subjected to simple stress, such as uniaxial tension, complex internal stress patterns are developed because of the tendency of some fibers to straighten while others become more strongly crimped. At the same time any twist in the yarns introduces torsional effects. The result is an exceedingly complex combination of tension, compression and shear interacting among fibers and matrix.

In all of the foregoing types of materials locked-in residual stresses occur in both fiber and matrix because of differential volume changes in matrix and fiber during cure. As is pointed out in preceding sections of this report, an exact analysis based even on elastic behavior has not been developed for clusters of straight fibers in a matrix, and still less for woven or otherwise deformed masses of fibers in a matrix.

If visco-elastic behavior occurs, as in the matrix, for example, leading to internal creep and relaxation, the problem becomes much more complex, and analyses are still more rudimentary. In any event, a rigorous analysis or clear understanding of the micromechanics of such composites does not now exist.

5.2.2. Elastic Analysis

From the standpoint of elastic theory, layers of materials as classified above may be considered in their over-all behavior to be essentially: (1) isotropic, as exemplified by the randomly-oriented fibrous types; (2) orthotropic, as in the woven materials and the parallel-filament unwoven materials; or (3) they may have some other angular configuration as in the braids.

A laminate may be composed of layers of only one of the above listed types; it may have layers of several types; or it may consist of layers of fibrous and nonfibrous materials. In any event, the layers are bonded together and constrained to act as a unit under imposed loads.

Several different assumptions are commonly employed in the analysis of fibrous types of laminates. In the case of filament-wound shells, it is commonly assumed that all stresses are taken by the filaments and that the matrix contributes nothing in the way of strength or stiffness. In this netting-type of analysis the further assumption is usually made that the fibers are inextensible. In the interests of minimum weight and maximum strength an attempt is often made to lay down such filaments in the wall of a shell in such a way as to maintain equal stress in all filaments at all points. This generally means that the filaments follow a geodesic pattern with respect to the contours of the shell, and, because such structures are frequently subjected only to tensile stresses, the design is isotensoid. The assumptions underlying this netting-analysis can lead to considerable simplification, but they raise questions concerning the internal behavior and the distribution of stresses within a laminate consisting of parallel filaments laid down in different directions.

Other approaches to the elastic analysis of laminates consisting of fibrous materials assume that the individual layers are isotropic or orthotropic and that, consequently, the elastic constants at various angles to the natural axes behave according to the elastic theory of such materials. It is further postulated that the sum of the internal stresses in a particle of such a laminate must balance the external stresses and that the strains in all parts of the particle are equal in a given direction. An analysis based on these assumptions may lead to different results with respect to internal stresses within and among the layers comprising the laminate than follow from the netting analysis.

Much of the theory of laminate behavior is strictly applicable when stresses in the fiber are tensile. When stresses are compressive, fibers tend to become unstable and to buckle. Now the ability of the matrix to support the fiber against elastic or inelastic buckling becomes important. The theory of such behavior is by no means complete, particularly when the fiber is not straight, as is often the case even in randomly-oriented chopped fiber or in parallel unwoven filaments. The problem is much more complex in woven and braided materials.

Stresses induced within a laminate by external loading when combined with residual stresses developed during fabrication may well lead to failure of some of the constituents at stresses lower than would be predicted on the basis of simple elastic theory. This is particularly true of cracking in the resin matrix in fibrous composites. It has often been noticed that cracking occurs in such a matrix at strains well below the level at which fracture takes place in the pure unfibered resin. For example, because of the highly directional character of the mechanical properties of orthotropic materials, the direct tensile or compressive stresses at a given point in different layers may be considerably different from the average stresses at that point. Similarly, because of a cross-elasticity effect and different positions of the neutral axis in different directions, bending in one direction can cause appreciable secondary stresses in the transverse direction. Interlaminar shear, as a result of transverse edgewise stresses, calls for different analysis than shear caused by in-plane stresses.

Failure mechanisms and modes are problems of micromechanics applied to laminates. Because of the complex geometry, little is known respecting this, particularly when combined stresses occur. Various theories have been proposed based upon simple addition of stress ratios, maximum strain, strain-energy, and other concepts. Until more is known of the micromechanics of failure of simple aggregations under simple stress, this aspect of laminate behavior will continue to be at least semi-empirical.

6.2.3. Visco-Elastic Behavior

The foregoing brief discussion indicates that a good deal more work needs to be done to clarify the analysis of internal or micro-mechanics of laminates, even in the elastic range. When visco-elastic behavior occurs, leading to internal redistribution of stress within a laminate because of creep or relaxation, the problem becomes much more complex and the theory of such behavior is virtually nonexistent. Nevertheless, for many structures it may be desirable to incorporate matrices that are soft and yielding enough to allow for such internal readjustment without rupturing the matrix. It should be possible to analyze the effect upon stress distribution.

To clarify the uncertainties that still exist respecting the internal stress behavior of laminates incorporating fibrous composites will require a thoroughgoing theoretical and experimental research program. Because of the complexity of the problem of even a few fibers in a matrix, as brought out in earlier sections of this report, it is not likely that exact theories of elastic or visco-elastic behavior of fibrous composite laminates will soon be forthcoming. Consequently, theory and experiment must go forward together, each augmenting, clarifying, and giving direction to the other as knowledge of these materials becomes more complete, their consequent applications in end items improved, and their capabilities more fully exploited.

6.3. Recommendations

6.3.1. Theory and analysis should be vigorously prosecuted in the following directions:

(a) Internal elastic stress distribution in the layers of fibrous-based and combined fibrous and nonfibrous laminates when subjected to:

Simple tension

Simple compression

Shear

Flexure

Combined stresses.

(b) Stresses set up in the bond layer between layers of a laminate under the external stresses listed above.

(c) Theories of failure under simple and combined stress.

(d) Effect of changing temperature upon stress distribution when fibers and matrices have different thermal coefficients of expansion.

(e) Time-dependence in materials showing time-dependent behavior, i.e., visco-elastic behavior

Rates from impact to creep, relaxation;

Redistribution of stresses and strain among constituents of the laminate.

6.3.2. Experimental programs to check the theory and analysis as outlined above, to provide experimental values for the strength values, elastic constants, and visco-elastic functions employed, and to clarify and give direction to continuing analysis. Test values and experimental checks are particularly needed for:

Strength in tension, compression, shear, flexure, as function of fiber direction, type of fabric or weave.

Rate effects.

Behavior under combined stress.

Interlaminar stress, failure.

Repeated stress.

Temperature effects upon foregoing.

Prestressing of certain components, e.g., initial tension in fibrous components of laminate, inducing compression in other, possibly nonfibrous components. Effect upon internal stresses when subsequent loads are applied.

6.3.3. These parallel programs of analysis and experiment should be carried on simultaneously with the research into the micromechanics of fiber-matrix interactions outlined in earlier portions of this report. It is to be expected that as the fiber-matrix interaction is clarified, and as the problems of stresses at the interface are elucidated, considerable light will be thrown upon the problems of internal mechanics of laminates.

6.3.4. A corollary problem, although not strictly micromechanics, arises from the fact that the actual orientation of the layers of a laminate can be arranged so as most suitably and efficiently to resist the imposed stresses. This means, in effect, minimizing the internal stresses so as to maximize the external loads that can be carried without failure. The calculation can be tedious, especially for multi-layer laminates.

Quick machine-methods of computation need to be developed; these in turn depend upon the development of basic theory and analysis, checked by experiment and test, as outlined above.

6.4 Selected Bibliography for Laminates

1. Bouc, C. A., "Microscopic Study of Mode of Fracture in Filament Wound Glass-Resin Composites," TAM Report No. 234, University of Illinois, November 1962.

2. Chambers, R. E. and McGarry, F. J., "Shear Effects in Glass Fiber Reinforced Plastic Laminates," ASTM Bull. 38, May 1959.

3. Corten, H. T. (University of Illinois), "Progress Report on Mechanics of Failure of Glass Fiber Reinforced Plastics," 2nd Semi-Annual Polaris Glass Reinforced Plastics Research and Development Conference, January 1962.

4. Corten, H. T., Chapter 14, "Reinforced Plastics in Engineering Design for Plastics," edited by Eric Baer, Reinhold, 1964.

5. Dietz, A. G. H. (Editor), "Engineering Laminates," Wiley, 1949.

6. Dow, N. F. and Rosen, B. W., "Evaluations of Filament-Reinforced Composites for Aerospace Structural Applications," Annual Report, Contract NASw-817, General Electric Co., Space Sciences Lab., Missile and Space Division, Philadelphia, Pa., 26 Oct 1964.

7. Forest Products Laboratory, U.S. Dept. of Agriculture, Madison, Wisconsin. Numerous mimeograph reports on reinforced plastics.

8. Griffith, A. A., "The Phenomena of Rupture and Flow in Solids," Phil. Trans. Roy. Soc., London, 221, 163, 1921.

9. Haslett, W. H. and McGarry, F. J., "Shrinkage Stresses in Glass Filament-Resin Systems," Proc. SP , 17th Annual Conference, Sec. 14D, February 1962.

10. Hearmon, R. F. S., "An Introduction to Applied Anisotropic Elasticity," Oxford University Press, London, 1961.

11. Hill, R., "Theory of Mechanical Properties of Fibre-Strengthened Materials: 1. Elastic Behaviors," J. Mech. & Phys. of Solids, Vol. 12, pp. 199-212, 1964.

12. Love, A. E. H., "A Treatise on the Mathematical Theory of Elasticity," Fourth Edition, Chapter VI, Dover, 1944.

6.4. References (Continued)

13. McGarry, F. J., "Investigation of Mechanics of Reinforced Plastics," MCA-MIT Plastics Res. Proj. Progress Report. MIT 8225-3, June 15, 1959.

14. Melvin, J. W., "Effect of Resin Properties on the Fracture of FRP Laminate Models," TAM Report in preparation, Univ. of Illinois.

15. Peterson, G. P., "Engineering Properties of High Modulus Reinforced Plastics," Proc. SPI, 17th Annual Conference, Section 1A, February 1962.

16. Pipkin, A. C. and Rivlin, R. S., "Minimum-Weight Design for Pressure Vessels Reinforced with Inextensible Fibers," J. Applied Mechanics, March 1963.

17. "Plastics for Aircraft," ANC-17 Bull. Part I, "Reinforced Plastics," Superintendent of Documents, U.S. Government Printing Office, Washington, D. C., June 1955.

18. Rawe, R. A., "Crase Cracking and Associated Phenomena in Glass Filament Wound Pressure Chambers," Report No. M2099, Structural Material Div., Aerojet Gen. Corp., April 1961.

19. Rivlin, R. S. and Ginensky, S. M., "Infinitesimal Plane Strains in a Network of Elastic Cords," Archive for Rational Mechanics and Analysis, Vol. 4, No. 1, 1959.

20. Rosato, D. V. and Grove, Jr., C. S., "Filament Winding," Interscience, 1964.

21. Rosen, B. Walter, "Mechanics of Composite Strengthening," Technical Information Series R64SD80, Space Sciences Lab., Missile and Space Div., General Electric Co., Philadelphia, Pennsylvania.

22. Schuerch, H. U., Burggraf, O. R. and Kyser, A. C., "A Theory and Applications of Filamentary Structures - Part I: Theoretical Studies," Rept. ARC-R-30, Astro Research Corp., Sept. 1961.

23. Schuerch, H. U. and Burggraf, O. R., "Analytical Design for Optimum Filamentary Pressure Vessels," AIAA Journal, Vol. 2, No. 5, May 1964.

24. Schulz, J. C., "Maximum Stresses and Strains in the Resin of a Filament-Wound Structure," Proc. SPI, 18th Annual Conference, Sec. 7D, 1963.

6.4. References (Continued)

25. Sonneborn, R. H., "Fiberglass Reinforced Plastics," Reinhold Publishing Co., New York, N.Y., 1954.

26. Stavsky, Yehuda, "On the Theory of Heterogeneous Anisotropic Plates," MCA-MIT Plastics Res. Project, July 15, 1959.

27. Tsai, Stephen W., "Structural Behavior of Composite Materials," NASA Contractor Report, NASA CR-71, Contract No. NAS 7-215, Philco Corp., July 1964.

28. Werren, F. and Norris, C. B., "Mechanical Properties of a Laminate Designed to be Isotropic," Forest Products Lab. Report No. 1841, May 1953.

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
National Academy of Sciences
National Research Council
Materials Advisory Board
2101 Constitution Ave., N.W., Washington, D.C. 20418

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE

MICROMECHANICS OF FIBROUS COMPOSITES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report

5. AUTHOR(S) (Last name, first name, initial)

Materials Advisory Board Ad Hoc Committee on Micromechanics of Fibrous Composites

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1965	123	162

8a. CONTRACT OR GRANT NO.
ARPA SD-118

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
MAB 207-M

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
None

10. AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC.

11. SUPPLEMENTARY NOTES
None

12. SPONSORING MILITARY ACTIVITY
ODDR&E, The Pentagon, Washington, D. C.

13. ABSTRACT When external loads or other stress-inducing forces are applied to a composite of fibers embedded in a matrix, internal stresses are set up in each constituent and at the same time complex interactions occur between them. The study of these internal stresses, the internal mechanics of the reactions of the constituents, separately and in concert, to the imposed forces, may be called the micromechanics of fibrous composites. The reasons for theoretical and experimental research in micromechanics are, (1) to clarify the behavior of fibrous composites and thereby to improve the design of engineering structures based on them, and (2) to improve the properties of composites. In this study, the subject is divided into six areas. Certain aspects of each area are treated with respect to the significance of the area, the state of present knowledge (as available to the Committee), the still unanswered questions, and, to the extent possible, suggested lines of attack for research.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Composite						
Fibrous Composite						
Laminates						
Mechanics						
Internal mechanics						
Micromechanics						
Analysis						
Elastic analysis						
Inelastic analysis						
Composite design						
Constituent properties						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (*corporate author*) issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (*either by the originator or by the sponsor*), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (*paying for*) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (*TS*), (*S*), (*C*), or (*U*).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, non-profit organization of distinguished scientists and engineers dedicated to the furtherance of science and its use for the general welfare. The Academy itself was established by a Congressional Act of Incorporation, signed by Abraham Lincoln on March 3, 1863. Each year, the Academy elects up to 35 U.S. scientists and engineers to its membership, selected for their outstanding contributions to knowledge. Its members now number almost 700.

Under the terms of its Congressional charter, the Academy is called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science or technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency.

The National Research Council was organized by the Academy in 1916, at the request of President Wilson, to enable the broad community of U.S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the Academy, are drawn from academic, industrial, and government organizations throughout the country.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by more than 3,000 of the nation's leading scientists and engineers, the Academy and its Research Council thus work to serve the national interest, to foster the sound development of science and its applications, and to promote their effective utilization for the benefit of society.

THE MATERIALS ADVISORY BOARD is a unit of the Division of Engineering and Industrial Research of the National Academy of Sciences—National Research Council. It was organized in 1951 under the name of the Metallurgical Advisory Board to provide to the Academy advisory services and studies in the broad field of metallurgical science and technology. Since the organization date, the scope has been expanded to include organic and inorganic nonmetallic materials, and the name has been changed to the Materials Advisory Board.

Under a contract between the Office of the Secretary of Defense and the National Academy of Sciences, the Board's present assignment is

> **". . . to conduct studies, surveys, make critical analyses, and prepare and furnish to the Director of Defense Research and Engineering advisory and technical reports, with respect to the entire field of materials research, including the planning phases thereof."**